DESCRIPTION OF THE CEREBRAL VASCULATURE IN A SOUTHERN AFRICAN CADAVER COHORT

by

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Thesis presented in partial fulfilment of the requirments for the degree

Master of Science in Anatomy at

Stellenbosch University

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Faculty of Medicine and Health Sciences

March 2016

DECLARATION

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ABSTRACT

Few studies give a complete description on the origin, absence, duplication and triplication of the cerebral cortical branches. The anterior cerebral artery (ACA) varies considerably and this complicates the description of the normal anatomy. The most commonly discussed branching types of the middle cerebral artery (MCA) include bifurcation and trifurcation. Branching of the posterior cerebral artery (PCA) has not been adequately described; only the division level of the parieto-occipital (PoA) and calcarine arteries has been discussed. Anomalies of the cerebral arteries have been reported. To the author's best knowledge, no previous studies have investigated the anatomy of the cerebral arteries in a Western Cape population. Therefore, the aim of this study is to describe the anatomy and anomalies of the cerebral vasculature in a Southern African cadaver cohort.

Twenty hemispheres were used for the pilot study and 126 hemispheres for the present study. These 126 hemispheres consisted of 88 males and 38 females, between the ages of 22 and 84. Specimens were distributed over three population groups, namely, coloured (n=76), black (n=38), white (n=10) and unknown (n=2). The arteries were injected with coloured silicone. The external diameter and length of all the cortical branches of the cerebral arteries were measured using a digital micrometre.

The diameter and lengths indicated statistically significant differences on the right and left side, between males and females, different population groups and different age groups. The most commonly absent artery was the callosomarginal artery, and the most commonly duplicated artery was the paracentral lobule artery. The origin of the cortical branches was similar to the descriptions in the literature; however, the common trunks and unusual origins were also noted. The branching pattern of the MCA was classified according to the 11 different subtypes described in the literature. Medial bifurcation was most commonly observed. The branching pattern of the PCA was assessed, and in most cases there was additional branching before the division of the calcarine artery and PoA. Anomalies observed in the present study included bihemispheric ACA (19.8%), median ACA (11.6%) and fenestration of the PCA (1.6%). The only anomaly observed in the pilot study was fenestration of the PCA (5.0%).

A shorter trunk may play a role in aneurysm formation, and changes in vessel diameter could indicate early signs of several pathological conditions. Aneurysms can be observed at the branching of cerebral vessels, highlighting the importance of a thorough knowledge of the vascular anatomy. The MCA branching subtypes were described, since only bifurcation and trifurcation are usually noted. Furthermore, the branching pattern of the PCA has not been adequately described in previous reports;

therefore the possible branching types were defined. Anomalies of the cerebral arteries are usually only mentioned; therefore the bihemispheric and median ACA were fully described (origin, length, diameter and area supplied). Given the important implications that the anatomical variation of the cerebral arteries may have, future research should focus on giving a more comprehensive description of the anatomy.

OPSOMMING

Min studies bied 'n volledige beskrywing van die oorsprong, afwesigheid, duplisering en triplisering van die serebrale kortikale arteries. Die verloop van die anterior serebrale arterie (ASA) varieer aansienlik wat beskrywing van die normale anatomie bemoeilik. Die mees algemeenste vertakkingstipes van die middel serebrale arterie (MSA) sluit bifurkasie en trifurkasie in. Vertakking van die posterior serebrale arterie (PSA) word nie voldoende beskryf nie; slegs die vlak van die oorsprong van die parieto-oksipitaal (PoA) en kalkariene arteries word bespreek. Variasies in die anatomie van die serebrale arteries kan waargeneem word. Sover die kennis van die outeur strek, is geen studies oor die anatomie van die serebrale arteries voorheen op 'n Wes-Kaapse populasiegroep voltooi nie. Die doel van hierdie studie is om die kortikale arteries in 'n Suid-Afrikaanse kadawer populasie te beskryf.

Twintig hemisfere is vir die loodsstudie en 126 hemisfere vir die huidige studie gebruik. Die 126 hemisfere het bestaan uit 88 mans en 38 vrouens, tussen die ouderdom van 22 en 84 jaar. Die studiepopulasie het bestaan uit drie populasie groepe; kleurling (n=76), swart (n=38), wit (n=10) en onbekende (n=2) groepe. Die arteries is met gekleurde silikoon ingespuit. Die eksterne deursnit en lengte van al die kortikale arteries is met 'n digitale mikrometer gemeet.

Die deursnit en lengtes het statisties beduidende verskille tussen links en regs, mans en vrouens, verskillende populasiegroepe en verskillende ouderdomsgroepe getoon. Die kallosomarginale arterie was oor die algemeen die meeste afwesig, en die parasentrale lobule arterie was die mees algemeenste arterie wat verdubbeld is. Alhoewel gemeenskaplike stamme en ongewone oorspronge ook opgemerk is, is die oorspronge van die kortikale arteries soortgelyk aan beskrywings wat in die literatuur voorkom. Die vertakkingspatroon van die MSA is volgens die 11 verskillende subtipes wat in die literatuur beskryf is, geklassifiseer. Mediale bifurkasie is die meeste waargeneem. Die vertakkingspatroon van die PSA is geëvalueer, en in die meeste gevalle was daar 'n bykomende vertakking voor verdeling van die PoA en kalkariene arterie. Abnormale variasies wat in die huidige studie waargeneem is sluit ‘n bihemisferiese ASA (19.8%),’n mediaane ASA (11.6%) en fenestrasie in die PSA (1.6%) in. Die enigste abnormale variasie wat in die loodsstudie waargeneem is, was fenestrasie in die PSA (5.0%).

‘n Korter arteriële stam kan 'n rol speel in die vorming van aneurismes, en veranderinge in die deursnit kan vroeë tekens van verskeie patologiese toestande aandui. Aneurismes word dikwels by die vertakking van serebrale arteries waargeneem, wat die belang van 'n deeglike kennis van die vaskulêre anatomie beklemtoon. Die vertakking subtipes van die MSA is deeglik beskryf, aangesien slegs bifurkasie en trifurkasie gewoonlik in die literatuur bespreek word. Die vertakkingspatroon van die PSA

is nie voldoende in vorige studies beskryf nie; dus is al die moontlike vertakkingstipes gedefinieer. Abnormale variasie van die serebrale arteries word gewoonlik net genoem; dus is die bihemisferiese en mediaane ASA volledig beskryf (oorsprong, lengte, deursnit en area van voorsiening). Gegewe die implikasies van anatomiese variasies van die serebrale arteries, behoort toekomstige navorsing te fokus op 'n meer omvattende beskrywing van die anatomie.

ACKNOWLEDGEMENTS

Firstly I would like to thank God for His presence in my life. I would also like to thank my supervisor, Prof BJ Page. Thank you to the University of Stellenbosch and the Division of Anatomy and Histology for financial assistance and for the opportunity to attend and present a poster at the 17th International Conference on Microscopic and Macroscopic Anatomy in Barcelona, Spain. I am grateful for the opportunity to publish a part of this thesis, in an upcoming issue of Turkish Neurosurgery.

I am thankful for the financial support of the Harry Crossley Foundation, without this financial support this project would not have been possible. I am also thankful for the financial support during my masters from Prof NC Gey van Pittius. I am grateful to Mr MT Chirehwa for statistical analysis and I would like to thank Mrs LM Greyling, Dr E Geldenhuys and Ms PC Kotze for editing.

Thank you to Mr RP Williams, Mr A Marthie and the Honours students for technical assistance with removal of the brains. A special thanks to Ms J Walters and Mr RP Williams for assistance with perfusion. I am grateful for the continuous support of the Masters students and for the support of family and friends.

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ABBREVIATIONS

AA	Angular artery
ACA	Anterior cerebral artery
AChA	Anterior choroidal artery
AcoA	Anterior communicating artery
AIFA	Anterior internal frontal artery (Anteromedial frontal branch)
AITA	Anterior inferior temporal artery
APA	Anterior parietal artery
ATA	Anterior temporal artery
BihemACA	Bihemispheric anterior cerebral artery
CA	Central artery
CmA	Callosomarginal artery
EFB	Early frontal branch
ETB	Early temporal branch
FpA	Frontopolar artery (Polar frontal artery)
IFA	Internal frontal artery
IfO	Infra-orbital artery (Medial orbitofrontal artery)
IIPA	Inferior internal parietal artery
MCA	Middle cerebral artery
MedACA	Median anterior cerebral artery
MIFA	Middle internal frontal artery (Intermediomedial frontal branch)
MITA	Middle inferior temporal artery
MTA	Middle temporal artery
OfA	Orbitofrontal artery (Lateral orbitofrontal artery)
PCA	Posterior cerebral artery
PcA	Precentral artery
PfA	Prefrontal artery
PIFA	Posterior internal frontal artery (Posteromedial frontal branch)
PITA	Posterior inferior temporal artery
PLA	Paracentral lobule artery
PoA	Parieto-occipital artery

PPA	Posterior parietal artery
PrcA	Pericallosal artery
PTA	Posterior temporal artery
RaH	Recurrent artery of Heubner
SA	Splenial artery
SIPA	Superior internal parietal artery
ToA	Temporo-occipital artery
TpA	Temporopolar artery (Polar temporal artery)

CHAPTER ONE

INTRODUCTION

The cerebral cortex is primarily supplied by the anterior, middle and posterior cerebral arteries. The anterior cerebral artery (ACA) and posterior cerebral artery (PCA) mainly supply the medial and posterior surface of the cerebral hemisphere, while the middle cerebral artery (MCA) supplies the lateral surface of the cerebral hemisphere[1].

The segmentation of the ACA is mostly agreed on by different authors, although the relationship of the pericallosal (PrcA) and callosomarginal arteries (CmA) is not agreed upon. The ACA varies considerably and this complicates the description of the normal anatomy[2]. The ACA may have a more simplistic structure compared to the MCA, although more variations are observed in the ACA compared to the MCA[2-6]. The branches of the MCA cover a large part of the lateral surface of each hemisphere; therefore it is likely to be exposed during surgical intervention in this area[7, 8]. Segments of the MCA are similarly described by most authors; however, there is still some disagreement on the branching pattern of the MCA[5]. The posterior circulation is complex, tends to vary and very few studies have focussed on the anatomy of the PCA[9]. It is important to be aware of the possibility of variations, since these variations can have serious clinical implications. The knowledge of these variations can be helpful to clinicians and neurosurgeons[10].

The literature review gives an extensive summary of the cerebral segments and cortical branches. The different branching types and the cerebral anomalies were discussed. An extensive report on the prevalence of the cerebral anomalies was given. An illustration of the different MCA subtypes was provided since there is still confusion on these subtypes.

In the present study, a detailed analysis was done on the diameter and length of the cerebral segments and cortical branches to indicate possible statistically significant differences on the left and right side, between age, population groups, and sex. To the author's best knowledge, this has been poorly reported in previous studies. The pilot and present study also reported on the origins, absence, duplication and triplication of the cortical branches, since few studies have focussed on these aspects. The anatomy of the temporal superior and temporal inferior arteries have been scarcely documented, thus a detailed description was given on the anatomy of these arteries. Possible common trunks are also not thoroughly reported in the literature. These aspects were reported on in the pilot and present study. The criteria for each MCA branching subtype has not been previously described, thus this was noted in the pilot study. The prevalence of these branching subtypes was noted in the pilot and present study.

The PCA is the most neglected cerebral artery; therefore special attention was given on the anatomy of the PCA. A revised classification of the inferior temporal arteries, which excludes the hippocampal arteries, and takes into account the origins of the inferior temporal cortical branches of the PCA, was suggested. The branching pattern of the PCA has not been adequately described; therefore the branching pattern was re-evaluated and described as monofurcation, bifurcation and trifurcation.

More information was given on the origin, diameter, length and area supplied by the ACA anomalies and additional criteria were given to classify the ACA anomalies. To the author's best knowledge, this is the first study on the anatomy of the cerebral vasculature to be completed on a Western Cape population or in South Africa.

CHAPTER TWO

LITERATURE REVIEW

2.1. ANTERIOR CEREBRAL ARTERY

The anatomy of the anterior cerebral artery (ACA) varies considerably which complicates the description of the ACA and its branches. The segmentation of the ACA is described similarly by various authors[11-14], however, the relationship of the pericallosal (PrcA) and callosomarginal arteries (CmA) is not agreed upon[2].

2.1.1. Segmentation

Different terms and definitions are often used to describe the ACA segments[3, 11, 15]. The ACA can be divided into proximal and distal segments, or pre- and post-communicating segments. The ACA can also be described in three separate parts, namely the A1 segment (also referred to as the horizontal proximal or pre-communicating segment), the A2 segment (the vertical proximal or post-communicating segment), and the A3 segment (the distal parts and cortical branches)[13].

Most studies[8, 12-16], however, refer to the A1, A2, A3, A4 and A5 segments. The A1 segment runs from the origin of the ACA to the level of the AcoA. The pericallosal artery arises distal to the A1 segment and consists of several segments that can be divided according to their relationship with the corpus callosum. The A2 segment (also referred to as the infracallosal section) runs vertically from the anterior communicating artery (AcoA) to the genu of the corpus callosum. The A3 segment (also referred to as the precallosal part) curves around the genu, and the A4 segment (also referred to as the supracallosal section) usually runs in the sulcus of the corpus callosum and almost reaches the splenium[8, 12-14]. The A5 segment (cortical branches) varies considerably; it is therefore difficult to describe a standard arterial pattern for this segment[2]. The two basic configurations of the ACA are determined by the presence or absence of the CmA[12, 15, 16]. The different configurations and segments of the ACA are illustrated in Figure 2.1.

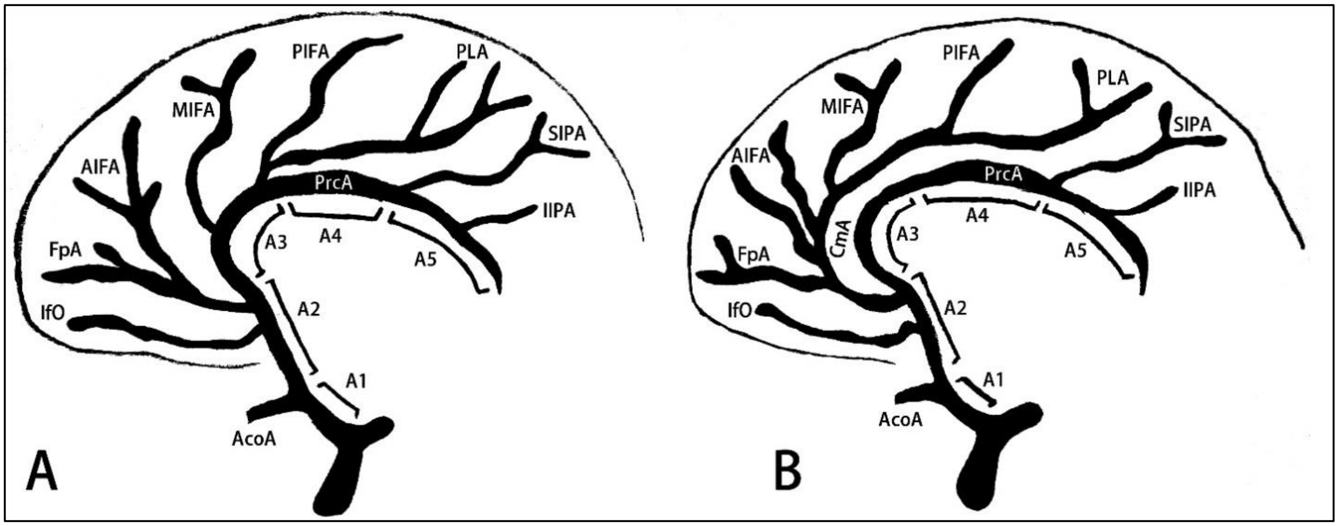

Figure 1.1: The different configurations of the anterior cerebral artery. A) Callosomarginal artery is absent; and B) Callosomarginal artery is present. (AcoA) Anterior communicating artery; (AIFA) Anterior internal frontal artery; (CmA) Callosomarginal artery; (FpA) Frontopolar artery; (IfO) Infra-orbital artery; (IIPA) Inferior internal parietal artery; (MIFA) Middle internal frontal artery; (PLA) Paracentral lobule artery; (PIFA) Posterior internal frontal artery; (PrcA) Pericallosal artery; and (SIPA) Superior internal parietal artery.

The A2 and A3 segments have collectively been referred to as the ascending or vertical segment and the A4 and A5 segments as the horizontal segment[14, 15]. The ACA have also been divided into a basal and a distal part. The basal part runs from the origin to the rostrum of the corpus callosum, and the distal part runs around the genu and superior to the corpus callosum[14].

Several authors refer to the A1 segment as the anterior cerebral artery and the artery distal to the AcoA as the pericallosal artery[3, 11, 14-16]. The A1 and A2 segments have also been referred to as the anterior cerebral artery and the artery distal to the origin of the callosomarginal artery, the pericallosal artery[14]. Since the origin of the CmA can vary, this terminology can be problematic[11]. Furthermore, the CmA is not always present, therefore it is preferable to classify the pericallosal artery as the part distal to the AcoA[8, 14, 17].

2.1.2. Cortical branches

The ACA cortical branches include the infra-orbital artery (IfO), frontopolar artery (FpA), anterior internal frontal artery (AIFA), middle internal frontal artery (MIFA), posterior internal frontal artery (PIFA), callosomarginal artery (CmA), paracentral lobule artery (PLA), superior internal parietal artery

(SIPA) and inferior internal parietal artery (IIPA). These branches can originate from the A2, A3, A4 and A5 segments as single branches or as common trunks.

2.1.2.1. Callosomarginal artery

The CmA can be seen as the largest branch of the pericallosal artery[16]. The CmA has been defined as the artery that runs in or near the cingulate sulcus and gives off two or more cortical branches. This definition is problematic since there can occasionally be more than one artery that arise from the pericallosal artery, run in the cingulate sulcus and give rise to a number of cortical branches[2].

In a study by Ugur *et al.*[2] a new classification system was proposed; the CmA was either defined as typical, atypical or absent. An atypical CmA was observed when there was only a very short artery coursing in the cingulate sulcus and two symmetrical callosomarginal arteries can also be present in the same hemisphere[2]. A typical CmA has a longer course compared to an atypical callosomarginal artery and usually originates from the A3 segment[2, 14, 17, 18]. The callosomarginal artery can originate from the A2 segment, A3 or A4 segment[8, 19]. Ugur *et al.*[2] observed typical, atypical and absent CmAs in 49.0%, 34.0% and 17.0% of cases respectively. The callosomarginal artery has been observed in 40.0% to 93.4% of specimens (Table 2.1)[2, 3, 14-18, 20-26]. The variability regarding the absence or presence of the CmA can be ascribed to the different definitions that are used for this artery[25].

2.1.2.2. Infra-orbital and frontopolar artery

The infra-orbital artery (IfO) normally originates from either the A2 segment, the callosomarginal artery or as a common trunk with the frontopolar artery[3, 11, 27, 28]. In rare cases the IfO can originate from the A1 segment or from the internal frontal arteries. The infra-orbital artery was present in 3.6% to 100% of cases in a number of studies (Table 2.1)[2, 3, 14-16, 21, 22]. Duplication of the IfO was observed in 6.0% (three cases)[15], 39.4% (15 cases)[3] and 42.0% (21 cases)[2] in the literature. Ugur *et al.*[2] observed three and four infra-orbital arteries in 16.0% and 4.0%, respectively. The frontopolar artery (FpA) usually arises from the A2 segment or callosomarginal artery[2, 3, 11, 27]. The FpA was present in 12.5% to 100% of cases in several studies (Table 2.1)[2, 3, 14, 16, 21, 22].

2.1.2.3. Internal frontal arteries

The anterior, middle and posterior internal frontal arteries usually arise separately, although the internal frontal branches can occasionally originate from a common trunk, referred to as the internal frontal artery

(IFA)[2]. Ugur *et al*.[2] found that the internal frontal artery was present in 58.0% (29 cases) of the study population. A number of studies[2, 3, 14, 16, 17, 21, 22] observed the anterior internal frontal artery (AIFA) in 33.9% to 100% of cases, the middle internal frontal artery (MIFA) in 64.3% to 100% of cases and the posterior internal frontal artery (PIFA) in 67.9% to 100% of cases (Table 2.2).

Table 1.1: The presence and origins of the infra-orbital, frontopolar and callosomarginal arteries[2, 14, 16, 17, 21, 22, 29, 30].

		Total	Presence	A1	A2	A3	A4	CmA	Special
IfO	**Perlmutter & Rhoton (1978)**	50	100%	-	82.5%	-	-	-	CT FpA: 18.0%
	Gomes *et al*. (1986)	30	100%	-	100%	-	-	-	-
	Kakou *et al*. (2000)	46	100%	17.0%	83.0%	-	-	-	-
	Avci *et al*. (2003)	62	100%	-	100%	-	-	-	-
	Ugur *et al*. (2006)	50	100%	1.0%	64.0%	-	-	-	-
	Kedia *et al*. (2013)	15	100%	16.3%	83.3%	-	-	-	-
FpA	**Perlmutter & Rhoton (1978)**	50	100%	-	90.0%	-	10.0%	-	-
	Gomes *et al*. (1986)	30	100%	-	100%	-	-	-	-
	Kakou *et al*. (2000)	46	100%	17.0%	65.0%	9.0%	9.0%	-	-
	Avci *et al*. (2003)	62	100%	-	95.0%	5.0%	-	-	-
	Ugur *et al*. (2006)	50	98.0%	-	72.0%	-	9.0%	-	IFA: 14.0%, AIFA: 3.0%
	Kedia *et al*. (2013)	15	100%	-	40.0%	56.6%	3.3%	-	-
CmA	**Perlmutter & Rhoton (1978)**	50	82.0%	-	12.2%	73.2%	-	14.6%	-
	Gomes *et al*. (1986)	30	91.6%	-	3.6%	90.9%	-	5.4%	-
	Kawashima *et al*. (2003)	22	91.0%	-	4.5%	91.0%	-		AcoA: 4.5%
	Ugur *et al*. (2006)	50	83.0%	-	18.0%	64.0%	-	12.0%	AcoA: 6.0%
	Cavalcanti *et al*. (2010)	60	93.3%	-	10.3%	55.2%	-	24.1%	AcoA: 10.3%
	Kedia *et al*. (2013)	15	93.4%	-	10.0%	50.0%	-	40.0%	-

(AcoA) Anterior communicating artery; (CmA) Callosomarginal artery; (CT) Common trunk; (FpA) Frontopolar artery; (IFA) Internal frontal artery; and (IfO) Infra-orbital artery.

Table 1.2: The presence and origins of the anterior, middle and posterior internal frontal arteries[2, 14, 17, 21, 22].

		Total	Presence	A2	A3	CmA	IFA	A4	Special
AIFA	**Perlmutter & Rhoton (1978)**	50	86.0%	16.3%	55.8%	27.9%	-	-	-
	Gomes *et al*. (1986)	30	96.6%	-	6.8%	84.4%	-	8.6%	-
	Kakou *et al*. (2000)	46	100%	-	65.0%	35.0%	-	-	-
	Ugur *et al*. (2006)	50	100%	4.0%	10.0%	18.0%	53.0%	-	FpA:15.0%
	Kedia *et al*. (2013)	15	100%	13.3%	60.0%	26.6%	-	-	-
MIFA	**Perlmutter & Rhoton (1978)**	50	90.0%	2.2%	46.7%	46.7%	-	4.4%	-
	Gomes *et al*. (1986)	30	98.3%	-	3.3%	77.9%	-	16.9%	A5: 1.6%
	Ugur *et al*. (2006)	50	100%	-	21.0%	25.0%	50.0%	-	FpA: 4.0%
	Kedia *et al*. (2013)	15	100%	-	43.3%	43.3%	-	13.4%	-
PIFA	**Perlmutter & Rhoton (1978)**	50	76.0%	-	31.6%	36.8%	-	31.6%	-
	Gomes *et al*. (1986)	30	91.6%	-	-	56.3%	-	36.3%	A5: 7.2%
	Ugur *et al*. (2006)	50	100%	-	12.0%	48.0%	32.0%	2.0%	PLA: 6.0%
	Kedia *et al*. (2013)	15	100%	-	10.0%	80.0%	-	10.0%	-

(AIFA) Anterior internal frontal artery; (CmA) Callosomarginal artery; (FpA) Frontopolar artery; (IFA) Internal frontal artery; (MIFA) Middle internal frontal artery; (PIFA) Posterior internal frontal artery; and (PLA) Paracentral lobule artery.

2.1.2.4. Paracentral lobule artery and internal parietal arteries

The paracentral lobule artery (PLA) can be viewed as the vessel with the most regular origin, course and area supplied, and was present in 53.6% to 100% of cases studied in the literature (Table 2.3)[2, 3, 14, 16, 21, 22].

The superior internal parietal artery (SIPA) normally originates from the A4 segment and runs to the precuneus[11]. Ugur *et al*.[2] found that the SIPA can also arise from the callosomarginal artery or the paracentral lobule artery. The inferior internal parietal artery (IIPA) originates from the A5 segment and runs to the lower third of the precuneus[11]. Numerous studies[2, 3, 14, 17, 21, 22] observed the SIPA in 78.0% to 100% of cases and the IIPA in 60.0% to 85.0% of cases (Table 2.3).

The diameter and length of the cortical branches of the ACA have been measured previously in the literature and this is depicted in Table 2.4. According to the literature[2, 3, 14, 16, 21, 22], the CmA is generally the largest cortical ACA branch, and the infra-orbital and IIPA are the smallest cortical branches.

Table 1.3: The presence and origins of the paracentral lobule artery and internal parietal arteries[2, 14, 17, 21, 22].

		Total	Presence	A3	CmA	A4	A5	Special
PLA	**Perlmutter & Rhoton (1978)**	50	90.0%	20.0%	28.9%	35.6%	15.6%	-
	Gomes *et al*. (1986)	30	98.3%	-	16.9%	33.8%	49.1%	-
	Kakou *et al*. (2000)	46	-	50.0%	50.0%	-	-	-
	Ugur *et al*. (2006)	50	100%	12.0%	66.0%	20.0%	-	IFA: 2.0%
	Kedia *et al*. (2013)	15	100%	-	93.4%	6.6%	-	-
SIPA	**Perlmutter & Rhoton (1978)**	50	78.0%	-	23.1%	12.8%	64.1%	-
	Gomes *et al*. (1986)	30	85.0%	-	-	-	100%	-
	Kakou *et al*. (2000)	46	100%	-	15.0%	35.0%	50.0%	-
	Ugur *et al*. (2006)	50	88.0%	3.0%	30.0%	33.0%	24.0%	PLA: 10.0%
	Kedia *et al*. (2013)	15	93.0%	-	-	80.0%	20.0%	-
IIPA	**Perlmutter & Rhoton (1978)**	50	64.0%	-	3.1%	16.6%	81.3%	-
	Gomes *et al*. (1986)	30	60.0%	-	-	-	100%	-
	Kakou *et al*. (2000)	46	67.0%	-	-	-	100%	-
	Ugur *et al*. (2006)	50	85.0%	-	-	10.0%	75.0%	SIPA: 15.0%
	Kedia *et al*. (2013)	15	60.0%	-	-	-	100%	-

(CmA) Callosomarginal artery; (IFA) Internal frontal artery; (IIPA) Inferior internal parietal artery; (PLA) Paracentral lobule artery; and (SIPA) Superior internal parietal artery.

Table 1.4: The average diameter (mm) and length (mm) of the anterior cerebral cortical branches[2, 3, 14, 16, 21, 22, 29].

Diameter	**IfO**	**FpA**	**CmA**	**IFA**	**AIFA**	**MIFA**	**PIFA**	**PLA**	**SIPA**	**IIPA**
Perlmutter & Rhoton (1978)	0.9	1.3	1.8	-	1.3	1.3	1.4	1.3	1.2	1.1
Gomes *et al*. (1986)	0.9	1.2	1.8	-	1.0	1.0	1.0	1.1	0.8	0.7
Stefani *et al*. (2000)	0.9	1.1	1.8	-	1.3	1.4	1.3	1.2	1.0	0.8
Ugur *et al*. (2006)	1.1	1.4	1.9	1.7	1.3	1.2	1.3	1.4	1.3	1.2
Cavalcanti *et al*. (2010)	0.6	0.9	1.5	-	1.1	1.1	1.0	1.0	1.1	-
Kedia *et al*. (2013)	0.2	0.5	1.1	-	0.4	0.4	0.3	0.3	0.3	0.2
Length	**IfO**	**FpA**	**CmA**	**IFA**	**AIFA**	**MIFA**	**PIFA**	**PLA**	**SIPA**	**IIPA**
Perlmutter & Rhoton (1978)	5.0	14.0	43.0	-	47.0	65.0	73.0	79.0	92.0	131.0
Stefani *et al*. (2000)	7.7	21.6	29.4	-	41.3	56.8	70.3	84.8	101.6	112.6
Avci *et al*. (2003)	6.0	14.6	-	-	-	-	-	-	-	-

(AIFA) Anterior internal frontal artery; (CmA) Callosomarginal artery; (FpA) Frontopolar artery; (IFA) Internal frontal artery; (IfO) Infra-orbital artery; (IIPA) Inferior internal parietal artery; (MIFA) Middle internal frontal artery; (PIFA) Posterior internal frontal artery; (PLA) Paracentral lobule artery; and (SIPA) Superior internal parietal artery.

2.1.3. Anomalies

The anomalies of the distal ACA have been divided into three major groups (Fig. 2.2). These anomalies include an azygos ACA, bihemispheric ACA (BihemACA) and a median anterior cerebral artery (MedACA). Other variations include fenestrations, complete absence of a pericallosal artery and four pericallosal vessels[31, 32]. Duplication of the ACA bilaterally (four pericallosal vessels) was observed by Jain[33] in 0.3% (two cases) and Ozaki *et al*.[32] in 0.7% (one case). Ladziński *et al*.[34] observed an additional ACA branch that originated from the ipsilateral internal carotid artery. Burbank and Morris[35] observed a left ACA arising from the right internal carotid artery and noted that only one similar other case was described in the literature.

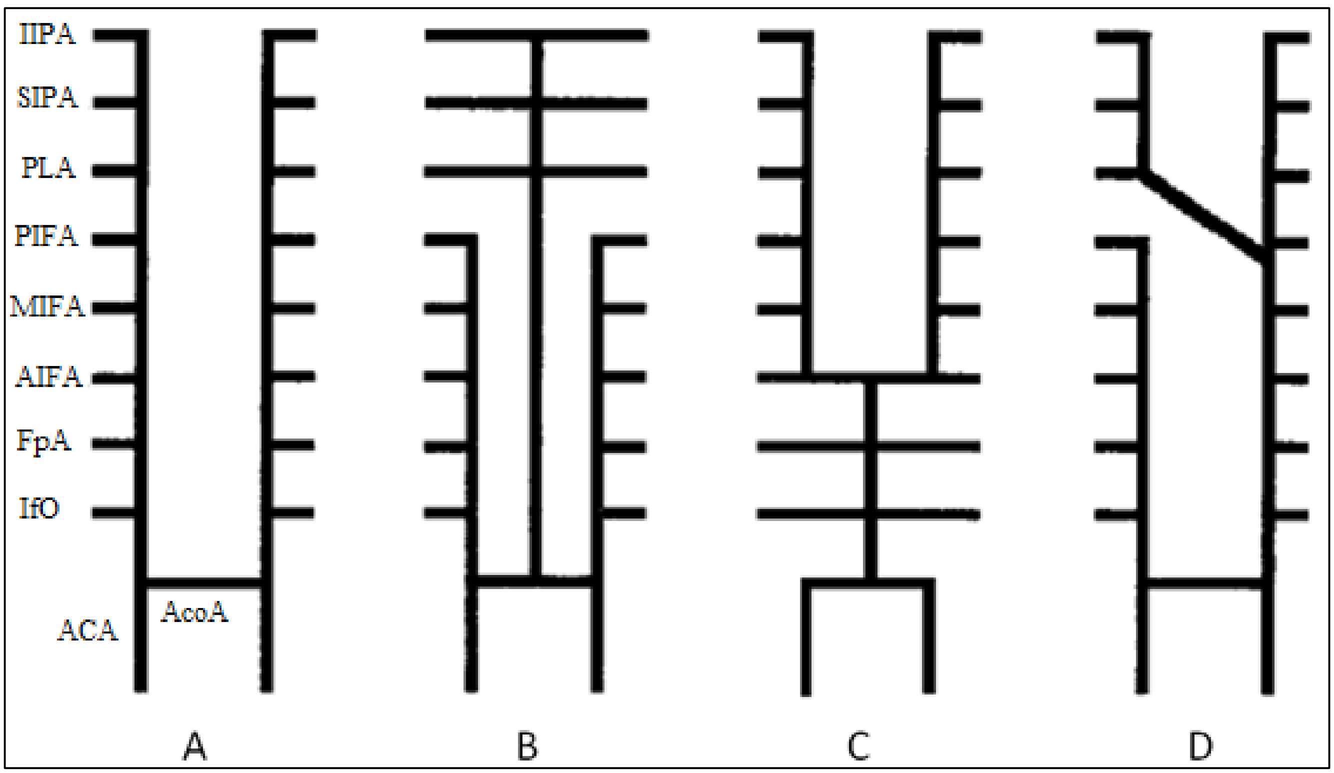

Figure 1.2: The different anomalous patterns of the anterior cerebral artery[3]. A) Normal pattern; B) Median anterior cerebral artery; C) Azygos anterior cerebral artery; and D) Bihemispheric anterior cerebral artery. (ACA) Anterior cerebral artery; (AcoA) Anterior communicating artery; (AIFA) Anterior internal frontal artery; (FpA) Frontopolar artery; (IfO) Infra-orbital artery; (IIPA) Inferior internal parietal artery; (MIFA) Middle internal frontal artery; (PIFA) Posterior internal frontal artery; (PLA) Paracentral lobule artery; and (SIPA) Superior internal parietal artery.

Most variations have no clinical relevance, although these anomalies may predispose patients to aneurysm formation. Occlusion of some of these anomalies can cause cerebral ischemia to both hemispheres[36].

2.1.3.1. Azygos anterior cerebral artery

The azygos ACA (Fig. 2.2) is formed by the fusion of the two A2 segments and runs along the medial surface of the hemispheres. It usually divides below the genu to supply both hemispheres[2, 11, 14, 16, 17, 19, 21-26, 28, 31, 32, 34, 35, 37-46]. The azygos ACA can also be formed when the embryonic median artery persists, along with lack of development of the A2 segments[46, 47].

The azygos ACA usually has little clinical significance[45], although this variation may be associated with other anomalies including agenesis of the corpus callosum, formation of arteriovenous malformations and ischemia[10, 48]. Some authors state that aneurysms are frequently associated with an azygos ACA[37, 39, 49], whereas others state that this association is extremely rare[50, 51]. Since this artery supplies parts of both hemispheres, occlusion may result in a large ischemic area[39, 45, 52]. The azygos ACA was observed in 0.04% to 10.0% (Table 2.5)[2, 3, 10, 19-21, 24, 36, 49, 51, 53-69] of cases studied.

The degree of fusion between the left and right ACA can vary from minor contact to a long single trunk[70, 71]. Kapoor *et al.*[62] noted that the trunk could be fused for 5.0 mm to 40.0 mm. When the arteries are fused for a shorter length, the variation can also be termed long fusion (an anterior communicating artery variation). Vasović[72] observed an azygos ACA that was fused for 3.3 mm and then divided into three arteries, the right and left A2 segments and a median anterior cerebral artery.

Gunnal *et al.*[10] divided the azygos ACA into five subgroups (Fig. 2.3). Type I is the classic or true azygos ACA while Type II consists of a shorter stem. Two A2 segments are described in Type III, although one terminates early. In Type IV there are two A2 segments, although one segment terminates as the callosomarginal artery. Type V is the median anterior cerebral artery[10]. In 112 specimens, Gunnal *et al.*[10] observed these five types in 2.7%, 1.8%, 3.6%, 2.7% and 0.9% respectively. The azygos ACA should not be confused with the bihemispheric ACA (classified as Type III and Type IV)[52, 68, 73].

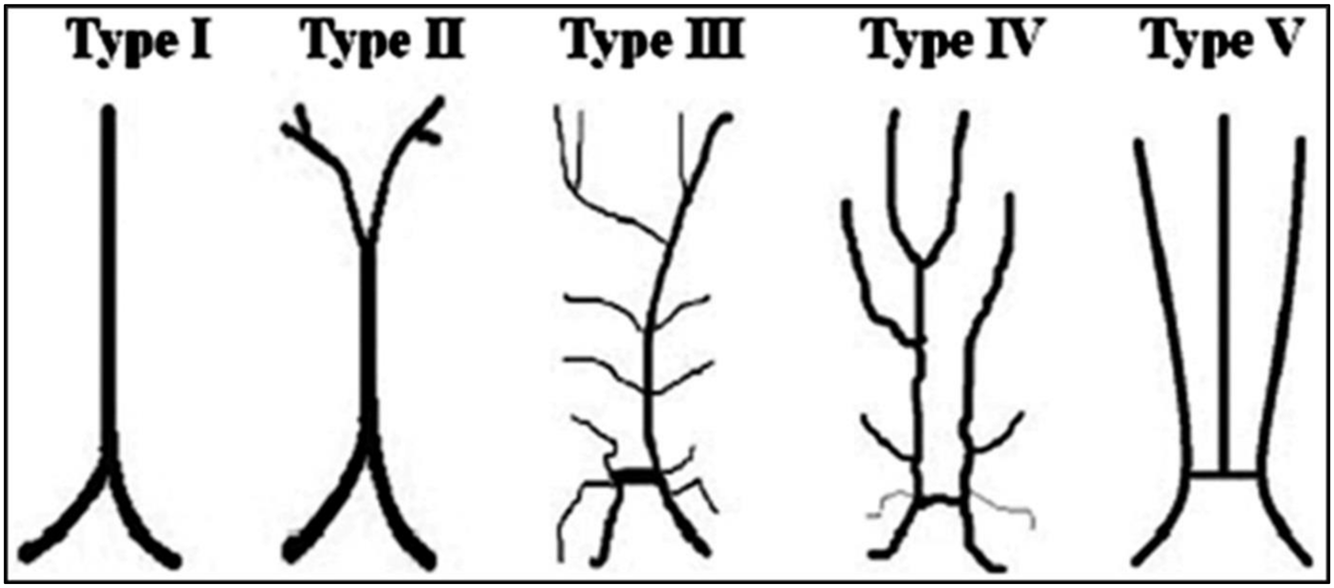

Figure 1.3: The five different types of the azygos anterior cerebral artery as described by Gunnal *et al*.[10].

The classic or true azygos anterior cerebral artery (Type 1) can be described as an artery that does not divide into two separate distal ACAs and gives rise to all cortical branches of both hemispheres. However, the azygos ACA typically divides close to the genu (Type II) into two pericallosal arteries to supply both hemispheres[10]. This variation is more commonly observed compared to the true azygos ACA[42].

2.1.3.2. Bihemispheric anterior cerebral artery

A bihemispheric ACA is classified when one A2 segment is hypoplastic (or terminates early) and the contralateral artery divides to supply both hemispheres (Fig. 2.2)[8, 13-15, 19, 41, 45, 46, 53]. A bihemispheric ACA was present in 0.9% to 64.0% (Table 2.5)[14, 15, 19, 20, 22, 25, 26, 36, 54, 61, 74-76] of specimens cited in the literature. Baptista[54] observed a case (0.3%) with a bihemispheric branch and a median anterior cerebral artery present.

2.1.3.3. Median anterior cerebral artery

When the median ACA is observed, a third distal ACA is present and can branch to the medial surface of one or both hemispheres (Fig. 2.2)[3, 11, 41, 46, 54, 62, 70, 77]. The median ACA usually curves around the genu and ends at the level of the body of the corpus callosum[78]. The cause is unknown, although this variation can be the result of the persistent or patent development of the median artery of corpus callosum, possibly due to a hypoplastic ACA[41, 45, 77]. A median ACA was present in 0.9% to 33.3%

(Table 2.5)[3, 19, 21, 22, 25, 26, 32, 33, 36, 49, 53, 54, 57, 59, 62, 64-69, 76, 78-87] of cases by previous authors. The average diameter of the median ACA was listed as 0.9 mm[88] and 1.3 mm[78].

The median anterior cerebral artery usually originates from the AcoA[8, 40, 42, 45, 67, 77, 79, 89]. In the literature the median ACA originated from the AcoA in 87.0%[62], 90.0%[78] and 100%[17, 22, 25, 32, 33, 69, 80, 88] of cases. Alternatively, the artery can originate from the junction of the A1 and A2 segments observed in 10.0%[78] and 13.0%[62] of cases.

2.1.3.4. Supreme anterior communicating artery

When an additional connection between the right and left A2 segments above the AcoA is present, this can be referred to as the supreme AcoA[10, 90]. The junction can also be termed the superior anterior communicating artery[91]. Laitinen and Snellman[90] observed this variation between the two pericallosal bifurcations. The supreme AcoA was observed in 20.0% (one case)[91] and 21.4% (three cases)[90] in the literature.

2.1.3.5. Fenestration

Fenestration occurs when the lumen of an artery is divided into two segments. It can also be referred to as partial duplication[46, 58, 92-94]. Both segments have an endothelium and muscular layer although the adventitia can be shared[46]. There are two types of fenestrations; small slit-like and large convex-like fenestrations and the small slit-like fenestration is the most common type[95].

These incomplete duplications are usually present in the vertebrobasilar region although it has been observed in the ACA[46, 58, 95-98]. The weakness of the wall of the fenestration and hemodynamic stress at these locations can play a role in aneurysm formation[68], thus there may be an association between aneurysms and fenestrations[99].

Fenestrations of the ACA usually occur at the distal part of the A1 segment[68, 96], specifically the distal half or two-thirds of the A1 segment[100-102]. Few authors specify in which part of the A1 segment the fenestration was observed. Ito *et al*.[103] stated that in all three cases they observed, the fenestration was located in the medial half of the A1 segment, while Yamada *et al*.[104] observed a fenestration in the middle part of the A1 segment. The cause is unknown; however, these fenestrations may be remnants of a plexiform anastomosis[45]. Fenestrations of the ACA were observed in the literature in 0.06% to 6.9%

(Table 2.5)[32, 36, 53, 55, 56, 58, 68, 99, 105-108] of cases previously studied. Figure 2.4 illustrates the different locations of the ACA fenestration.

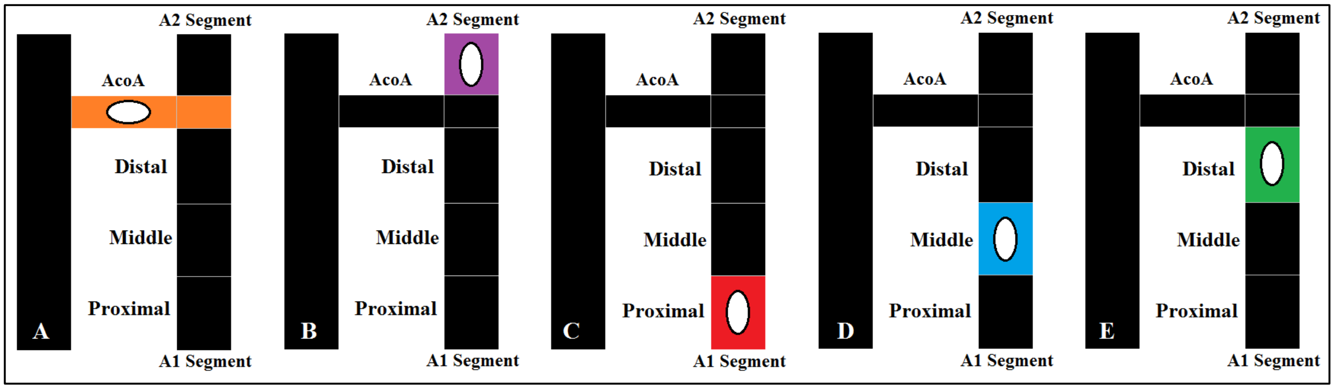

Figure 1.4: Anterior cerebral artery fenestrations. A) Anterior communicating artery fenestration; B) A2 segment fenestration; C) Proximal A1 segment fenestration; D) Middle A1 segment fenestration; and E) Distal A1 segment fenestration.

Very few authors specified whether the fenestrations were small slit-like or large convex-like fenestrations. Large convex-like fenestrations were observed in 1.0% (nine cases) and smaller slit-like fenestrations were observed in 0.2% (two cases) by Uchino *et al.*[68]. Fenestrations of the ACA on both sides are extremely rare[103], although Friedlander and Oglivy[109] and Vucetić[110] each reported a case of bilateral fenestration in the A1 segment.

Table 1.5: The prevalence of the azygos, bihemispheric, and median anterior cerebral arteries[2, 3, 10, 14, 15, 19-22, 24-26, 32, 33, 36, 49, 51, 53-69, 74-76, 78-87, 99, 105-108]**.**

	Total	Azygos ACA		BihemACA		Median ACA		Fenestration	
		Cases	%	Cases	%	Cases	%	Cases	%
Windle (1888)	200	6	3.0%	-	-	9	4.5%	-	-
Fawcett & Blachford (1905)	700	-	-	-	-	23	3.3%	-	-
Baptista (1963)	381	1	0.3%	45	11.8%	50	13.1%	-	-
Jain (1964)	300	-	-	-	-	26	8.7%	-	-
Fisher (1965)	414	7	1.7%	-	-	-	-	-	-
Lemay & Gooding (1966)	107	4	3.7%	-	-	-	-	-	-
Wollschlaeger *et al*. (1967)	291	3	1.0%	-	-	-	-	14	4.8%
Ring & Waddington (1968)	25	-	-	2	8.0%	-	-	-	-
Dunker & Harris (1976)	20	2	10.0%	-	-	-	-	-	-
Ozaki *et al*. (1977)	146	-	-	-	-	21	14.2%	3	2.1%
Perlmutter & Rhoton (1978)	25	-	-	16	64.0%	-	-	-	-
Tulleken (1978)	75	1	1.3%	-	-	8	10.7%	-	-
Huber *et al*. (1980)	7782	17	0.2%	-	-	-	-	-	-
Kwak *et al*. (1980)	296	-	-	-	-	13	4.4%	-	-
Kayembe *et al*. (1984)	44	-	-	-	-	10	22.7%	-	-
Gomes *et al*. (1986)	30	1	3.3%	-	-	1	3.3%	-	-
Marinković *et al*. (1990)	22	-	-	-	-	2	9.1%	-	-
Ogawa *et al*. (1990)	206	-	-	-	-	27	13.1%	-	-
Nathal *et al*. (1992)	134		%	-	-	5	3.7%	-	-
van der Zwan *et al*. (1992)	25	-	-	2	8.0%	-	-	-	-
Sanders *et al*. (1993)	5190	2	0.04%	-	-	-	-	3	0.06%
Macchi *et al*. (1996)	100	2	2.0%	-	-	9	9.0%	-	-
Serizawa *et al*. (1997)	30	1	3.3%	-	-	2	6.7%	-	-
Stefani *et al*. (2000)	38	1	2.6%	-	-	3	7.9%	-	-
Avci *et al*. (2001)	25	1	4.0%	-	-	1	4.0%	-	-
Kulenović *et al*. (2003)	1	-	-	-	-	1	1.0%	-	-
Paul & Mishra (2004)	50	-	-	1	2.0%	-	-	-	-
Ugur *et al*. (2005)	20	1	5.0%	1	5.0%	-	-	-	-
Tao *et al*. (2006)	45	-	-	-	-	1	2.2%	-	-
Uchino *et al*. (2006b)	891	18	2.0%	-	-	27	3.0%	11	1.2%
Ugur *et al*. (2006)	50	2	4.0%	-	-	-	-	-	-
Bharatha *et al*. (2008)	504	1	0.2%	-	-	-	-	35	6.9%
Kahilogullari *et al*. (2008)	30	-	-	-	-	10	33.3%	-	-
Kapoor *et al*. (2008)	1000	9	0.9%	-	-	23	2.3%	-	-
Lehecka *et al*. (2008)	101	4	4.0%	15	14.9%	4	4.0%	-	-
Saidi *et al*. (2008)	72	-	-	4	5.6%	-	-	-	-
Nowinski *et al*. (2009)	-	-	3.7%	-	-	-	-	-	-
Zurada *et al*. (2010)	115	2	1.7%	-	-	3	2.6%	-	-
Bayrak *et al*. (2011)	396	-	-	-	-	-	-	21	5.3%
Nordon & Rodrigues (2012)	50	-	-	-	-	3	6.0%	-	-
Sun *et al*. (2012)	4652	-	-	-	-	-	-	8	0.2%
Swetha (2012)	70	-	-	-	-	1	1.4%	-	-
Cilliers *et al*. (2013)	39	-	-	-	-	5	12.8%	-	-
Gunnal *et al*. (2013)	112	5	4.4%	7	6.3%	1	0.9%	-	-
Hamidi *et al*. (2013)	500	9	1.8%	9	1.8%	5	1.0%	12	2.4%
Kedia *et al*. (2013)	15	-	-	1	6.7%	1	6.7%	-	-
Stefani *et al*. (2013)	30	-	-	2	6.7%	1	3.3%	-	-
Cooke *et al*. (2014)	10927	-	-	-	-	-	-	43	0.4%
Kovač *et al*. (2014)	455	7	1.5%	4	0.9%	10	2.2%	3	0.7%
Vasović *et al*. 2014	266							13	4.9%
Wan-Yin *et al*. (2014)	3572	14	0.4%	-	-	-	-	-	-
van Rooij *et al*. (2015)	179	-	-	-	-	-	-	4	2.2%

2.2. MIDDLE CEREBRAL ARTERY

The middle cerebral artery (MCA) is the most complex cerebral artery; however, fewer anomalies are found compared to the other cerebral arteries[5, 6, 8, 27, 111-115]. The branches of the MCA cover a large part of the lateral surface of each hemisphere; therefore it is likely to be exposed during surgical intervention in this area[7, 8].

2.2.1. Segmentation

The MCA can be divided into four anatomical segments. These include the M1 segment (also referred to as the sphenoid or horizontal segment), the M2 or insular segment, the M3 or opercular segment, and the M4 segment or cortical branches[8, 11-13]. The different segments are illustrated in Figure 2.5.

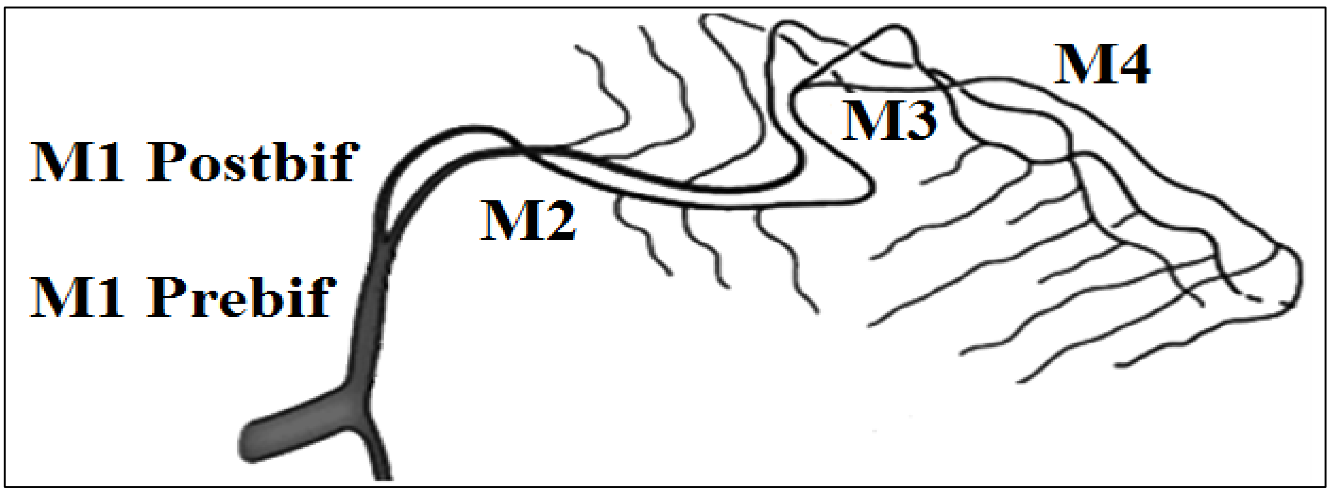

Figure 1.5: The different segments of the middle cerebral artery[13].

Some authors[7, 8, 12, 13] define the M1 segment as the section from the origin of the MCA to the genu (curve of the MCA), while others refer to the M1 segment as the part from the origin to the main branching. The M1 segment can be divided into the pre- and post-bifurcation segments (Fig. 2.5)[7, 12, 13]. The M2 segment begins when the MCA turns posterosuperiorly from the genu[11-13]. The M3 segment begins at the circular sulcus as the M2 segment turns laterally in the Sylvian fissure. The cortical branches (M4 segment) begin at the Sylvian fissure and extend over the surface of the hemispheres[7, 12].

2.2.2. Branching pattern

Various authors[11-13, 116] describe different branching types of the MCA and 11 different types can be distinguished from the literature (Fig. 2.6). The two most commonly observed configurations are the bifurcating and trifurcating patterns[13]. Tetrafurcation (also referred to as quadrafurcation), pseudotetrafurcation and a single trunk (monofurcation) have also been observed. When monofurcation (Fig. 2.6A) is present, a single trunk with no main branching is observed. Grellier *et al*.[116] described monofurcation as branching after the limen insulae.

The bifurcation branching type can further be divided into medial and lateral bifurcation (Fig. 2.6D and E), and medial and lateral pseudobifurcation (Fig. 2.6F and G). Medial and lateral branching refers to the distance of the branching from the MCA origin (branching close or further away, respectively). Pseudobifurcation (also referred to as false bifurcation) is when an artery originates from the main trunk (segment before initial branching) and gives a false impression of a bifurcation[11].

Grellier *et al*.[116] stated that the length of the main trunk could be divided into three types; short (3-12 mm), medium (13-22 mm) and long (23-40 mm). The short length could refer to early branching, although most authors[117-120] defined early branching as branching within 5 mm from the MCA origin. The medium and long length is similar to lateral and medial bifurcation described by Krayenbuhl *et al*.[11]; however, the authors did not state the lengths that were used to classify these bifurcation subtypes.

True trifurcation (Fig. 2.6H) is rarely observed, although the trifurcation subtypes (pseudotrifurcation, proximal trifurcation and distal trifurcation) are more commonly observed. In these subtypes the MCA bifurcates and the dominant branch subsequently bifurcates again to give rise to the middle branch. With pseudotrifurcation (Fig. 2.6I), the distance between the first and second bifurcation is less than 2 mm, and this subtype is observed least. It should be noted that this branching type can be classified as triplication in certain studies. With proximal trifurcation (Fig. 2.6J), the most common subtype, the distance between the first and second bifurcation is more than 2 mm. In distal trifurcation (Fig. 2.6K) the distance between the two bifurcations is more than 2 mm, and more than a quarter of the distance between the MCA origin and the first bifurcation[5].

Isolan *et al*.[115] described pseudotetrafurcation (Fig. 2.6C) as bifurcation of both the inferior and superior trunks near the initial bifurcation. This gives the false impression of a tetrafurcation (Fig. 2.6B) of the MCA[115]. The distance between the first and second bifurcation should be less than 2 mm.

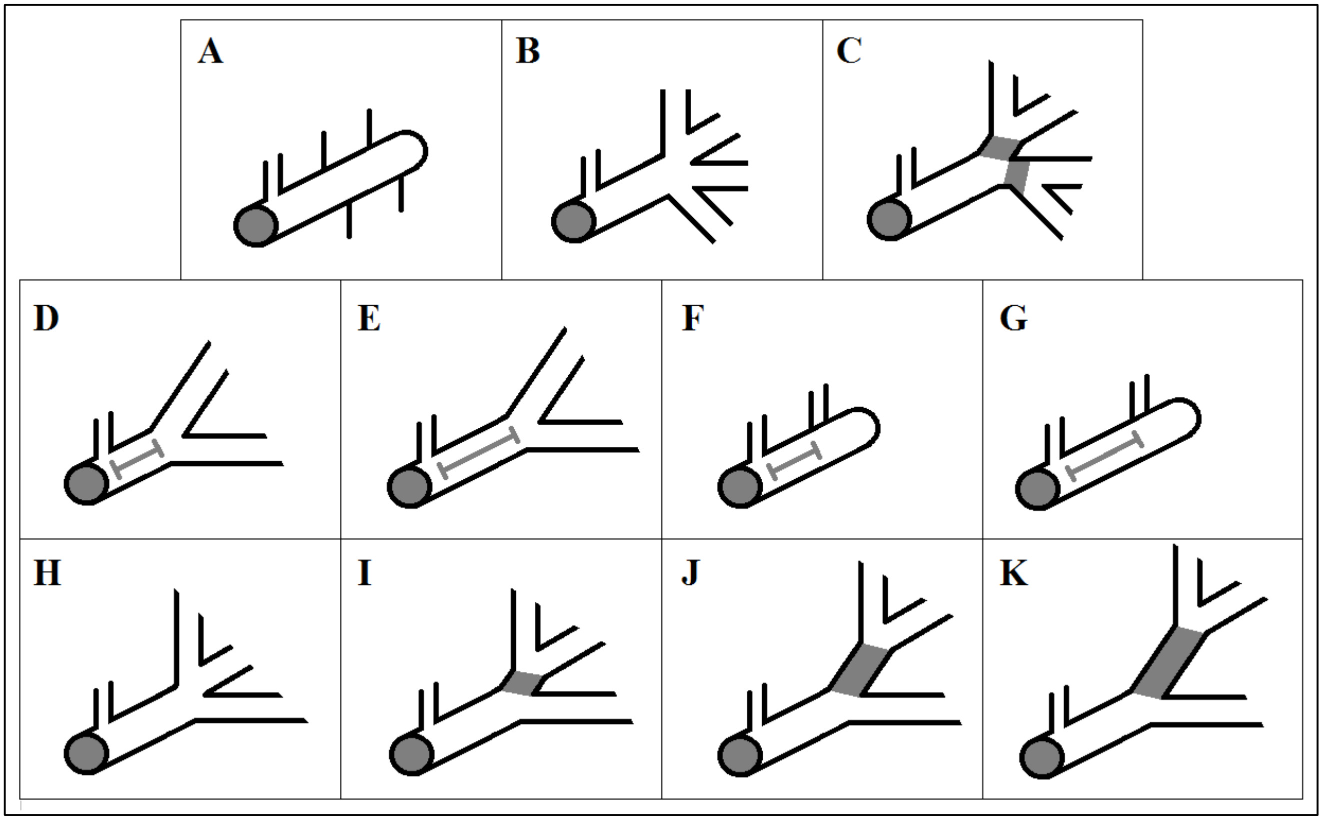

Figure 1.6: The 11 different branching patterns of the middle cerebral artery.
A) Monofurcation; B) Tetrafurcation; C) Pseudotetrafurcation; D) Medial bifurcation; E) Lateral bifurcation; F) Medial pseudobifurcation; G) Lateral pseudobifurcation; H) True trifurcation; I) Pseudotrifurcation; J) Proximal trifurcation; and K) Distal trifurcation.

Monofurcation was observed in 3.8% to 17.5%[113, 116, 119, 121-124] of cases in previous studies. Bifurcation was observed in 64.3% to 92.7%[5-7, 33, 80, 113, 114, 116, 119, 121-128] of cases, and trifurcation was found in 7.0% to 61.0%[5-7, 24, 33, 80, 113, 114, 116, 119, 121-129] of cases. Pseudotrifurcation was present in 3.0% (three cases)[129], 15.0% (five cases)[5] and 20.0% (two cases)[127]. Kahilogullari *et al*.[5] observed proximal trifurcation in 55.0% (18 cases) and distal trifurcation in 30.0% (ten cases). Tetrafurcation was observed in 0.7% to 10.0%[7, 119, 121, 122, 126] of cases, and pseudotetrafurcation was observed in 3.3% (one case)[115] of cases. The prevalence of the different branching patterns are summarised in Table 2.6; these varied observations can indicate that different definitions may be used by different authors for the classification of branching.

Table 1.6: The prevalence of monofurcation, bifurcation, trifurcation and tetrafurcation[6, 7, 24, 33, 80, 113, 114, 116, 119, 121-129].

		Monofurcation		Bifurcation		Trifurcation		Tetrafurcation	
	Total	**Cases**	**%**	**Cases**	**%**	**Cases**	**%**	**Cases**	**%**
Jain (1964)	300	-	-	270	90.0%	30	10.0%	-	-
Grellier *et al*. (1978)	280	49	17.5%	199	71.1%	32	11.4%	-	-
Gibo *et al*. (1981)	50	-	-	39	78.0%	6	12.0%	5	10.0%
Umansky *et al*. (1984)	70	4	5.7%	45	64.3%	20	28.6%	1	1.4%
Atunes (1985)	37	-	-	33	89.2%	4	10.8%	-	-
Umansky *et al*. (1985)	34	-	-	24	70.6%	7	20.6%	3	8.8%
Umansky *et al*. (1988)	104	4	3.8%	69	66.3%	27	26.0%	4	3.8%
Anderhuber *et al*. (1990)	100	-	-	-	-	7	7.0%	-	-
Meneses *et al*. (1997)	14	1	7.1%	12	85.7%	1	7.1%	-	-
Idowu *et al*. (2002)	100	6	6.0%	81	81.0%	13	13.0%	-	-
Kulenović *et al*. (2003)	-	-	-	-	70.0%	-	30.0%	-	-
Tanriover *et al*. (2003)	50	-	-	44	88.0%	6	12.0%	-	-
Tanriover *et al*. (2004)	43	-	-	38	88.4%	5	11.6%	-	-
Pai *et al*. (2005)	10	-	-	8	80.0%	-	-	-	-
Vuillier *et al*. (2008)	100	17	17.0%	73	73.0%	9	9.0%	-	-
Nowinski *et al*. (2009)	-	-	-	-	78.0%	-	12.0%	-	-
Ogeng'o *et al*. (2011)	288	18	6.3%	237	82.3%	31	10.8%	2	0.7%
Sadatomo *et al*. (2013)	124	-	-	115	92.7%	9	7.3%	-	-

2.2.3. Early branching

Early branching can be defined as branching within the first 5 mm from the origin of the MCA[117-120]. It has also been defined as branching that occurs within the proximal half of the M1 segment[130]. Teal *et al*.[117] observed three cases of early branching, one branched at 3 mm and two branched at 4 mm from the origin of the MCA. Early branching has been reported in 2.7% (one case)[125] 3.3% (five cases)[32], 5.1% (nine cases)[118], 5.2% (15 cases)[119], 5.3% (eight cases)[131] and 11.3% (five cases)[82] of cases in the literature. Early branching can be observed unilaterally or bilaterally[46].

2.2.4. Cortical branches

The MCA cortical branches include the orbitofrontal artery (OfA), prefrontal artery (PfA), precentral artery (PcA), central artery (CA), anterior and posterior parietal arteries, the angular artery (AA), the temporal arteries (temporopolar, anterior, middle and posterior temporal arteries) and temporo-occipital artery (ToA). These cortical branches can arise from the M1 segment and from the trunks that are formed by bifurcation or trifurcation[12]. The most common origins of the MCA cortical branches are illustrated in Figure 2.7.

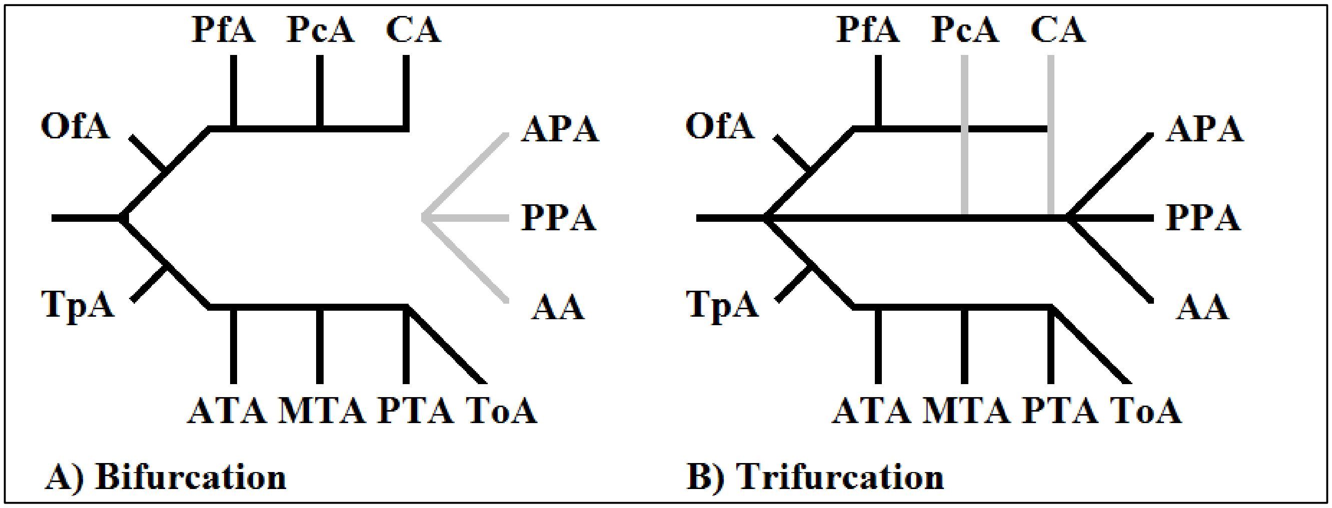

Figure 1.7: Illustration of the most common origins of the cortical branches originating from the superior, inferior and middle trunk (grey illustrates more than one typical origin).
(AA) Angular artery; (APA) Anterior parietal artery; (ATA) Anterior temporal artery; (CA) Central artery; (MTA) Middle temporal artery; (OfA) Orbitofrontal artery; (PcA) Precentral artery; (PfA) Prefrontal artery; (PPA) Posterior parietal artery; (PTA) Posterior temporal artery; (ToA) Temporo-occipital artery; and (TpA) Temporopolar artery.

2.2.4.1. Origins

If bifurcation occurs, the superior trunk usually gives rise to the OfA, prefrontal, precentral and central arteries, while the inferior trunk usually gives rise to the temporal and temporo-occipital arteries. The parietal and angular arteries can arise from the superior or the inferior trunk. In the case of the trifurcation pattern, the superior trunk usually gives rise to the OfA and prefrontal arteries, while the middle trunk usually gives rise to the parietal and angular arteries. The precentral and central arteries can originate from either the superior or the middle trunk. The inferior trunk usually gives rise to the temporal and temporo-occipital arteries[8, 11, 13, 27, 114, 121, 123, 132].

2.2.4.2. Early branches

Cortical branches that arise prior to the initial branching are referred to as early branches[7, 8]. The early branches can be divided into early temporal branches (ETB) and early frontal branches (EFB)[6, 7, 113, 119, 133]. Gibo *et al.*[7] observed 17 cases (34.0%) of ETB and five cases (10.0%) of early frontal branches, while Ogeng'o *et al.*[119] observed 184 cases (63.9%) of ETB and 104 cases (36.1%) of early frontal branches. The OfA, temporopolar artery and anterior temporal artery (ATA) commonly originate as early branches[7, 8].

Türe *et al*.[112] defined four configurations of early branches. In Type A only early temporal branches are present, in Type B both the frontal and temporal early branches are observed, and in Type C only early frontal branches are present. The Type D configuration is classified when no early branches are present. Rhoton[8] stated that there is usually only one early branch present, while Ciszek *et al*.[133] stated that an early frontal branch was most frequently located between two early temporal branches.

2.2.5. Anomalies

True anomalies of the MCA occur less frequently compared to anomalies of the other cerebral arteries[7, 12, 113, 115, 117, 122, 134-136]. The most common MCA anomalies include fenestration, and presence of a duplicated or an accessory middle cerebral artery (Fig. 2.8). An additional branch is present with both the duplicated and accessory middle cerebral arteries; an accessory MCA originates from the anterior cerebral artery, while a duplicated MCA arises from the internal carotid artery (ICA)[7, 11, 13, 41, 117]. The duplicated MCA usually supplies the temporal lobe and the accessory MCA typically supplies the frontal lobe[46, 115, 120, 136-139].

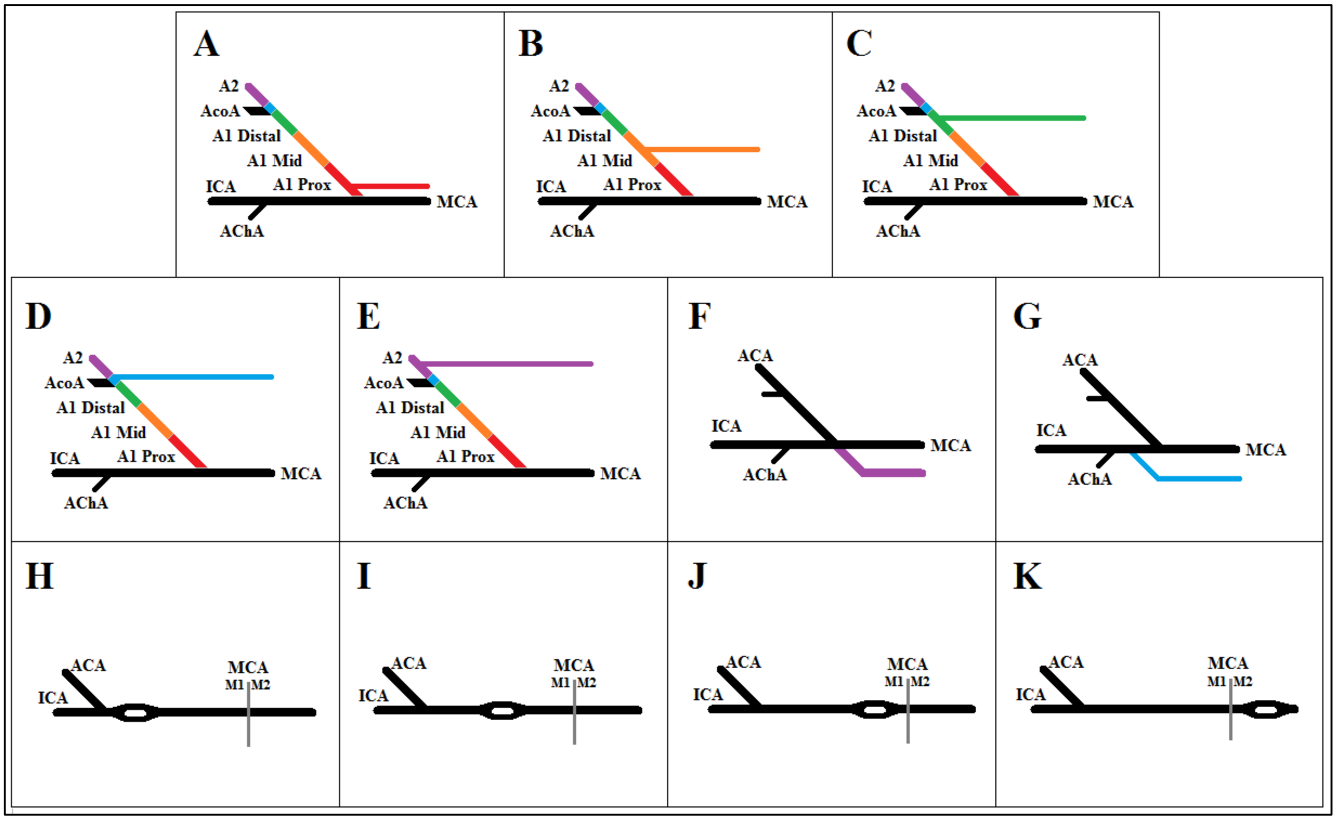

Figure 1.8: Anomalies of the middle cerebral artery. A) Accessory MCA from proximal A1 segment; B) Accessory MCA from middle A1 segment; C) Accessory MCA from distal A1 segment; D) Accessory MCA from AcoA level; E) Accessory MCA from A2 segment; F) Duplicated MCA Type A; G) Duplicated MCA Type B; H) Proximal M1 fenestration; I) Intermediate M1 fenestration; J) Distal M1 fenestration; and K) M2 segment fenestration. (AChA) Anterior choroidal artery; (AcoA) Anterior communicating artery; (ICA) Internal carotid artery; and (MCA) Middle cerebral artery.

Anomalies and variations can have serious clinical implications, therefore it is important to be aware of possible variants. The knowledge of these variations can be helpful to neurosurgeons and clinicians[10]. If the middle cerebral artery is occluded the accessory or duplicated MCA can offer potential collateral supply, however, the supply may not be adequate to completely avoid ischemia[33, 117, 119, 140].

2.2.5.1. Duplicated middle cerebral artery

The duplicated MCA can be classified into two types with regards to origin and diameter. The Type A duplicated MCA (most common) has a similar diameter compared to the main middle cerebral artery and arises at the top of the ICA (more distal origin). In Type B the duplicated MCA has a smaller diameter compared to the main middle cerebral artery and arises between the top of the ICA and anterior choroidal artery (more proximal origin)[141-143]. Type A can be viewed as an anomalous early arising MCA trunk, and Type B as an anomalous early arising MCA branch[144]. The two types are illustrated in Figure 2.8F and G. Most authors do not state the exact origin of the duplicated MCA, or whether Type A or Type B was observed.

The duplicated MCA was observed in 0.3% to 7.1% (Table 2.7)[6, 32, 33, 53, 116, 118, 119, 122, 123, 130, 131, 144-150] of cases in the literature. Kobari *et al*.[134] observed a triplicated MCA, with all three branches originating from the internal carotid artery. Lame *et al*.[151] observed a "crossover" duplicated MCA that originated from the left internal carotid artery and supplied the right hemisphere. Kai *et al*.[141] proposed that Type B might be more susceptible to aneurysm formation.

2.2.5.2. Accessory middle cerebral artery

The accessory MCA is typically smaller compared to a duplicated middle cerebral artery and supplies a smaller area[152]. The additional branch usually originates from the A1 segment close to the origin of the AcoA[6-8, 121, 140, 145, 153]. Accessory middle cerebral arteries can be classified into five types depending on the region of the ACA it arises from (Fig. 2.8A to E). The branch can arise from the proximal, middle or distal A1 segment, at the AcoA level, or from the A2 segment.

Uchino *et al*.[148] observed five cases with an accessory middle cerebral artery, four originating from the proximal A1 segment and one from the distal A1 segment. Kim *et al*.[150] observed one case arising from the proximal part and two cases originated from the distal part of the A1 segment. Few authors have described the accessory MCA originating from regions other than the proximal and distal A1 segment. Kim and Lee[154] stated that the accessory MCA originated from the middle A1 segment in two cases. This artery rarely arises from the A2 segment[135, 155] although Kim and Lee[154] observed this in one case. Additionally, Kahilogullari and Ugur[156] observed an accessory MCA that originated from the callosomarginal artery.

The accessory MCA was present in 0.1% to 9.1% (Table 2.7)[6, 32, 33, 36, 53, 55, 56, 82, 99, 105, 106, 113, 114, 116, 121-123, 130, 145, 147, 148, 150, 154, 157, 158] of cases. Two accessory middle cerebral arteries can also be present in one hemisphere[159] and Kim and Lee[154] observed one case of bilateral accessory MCAs. Gibo *et al*.[7] and Kitami *et al*.[147] observed a hemisphere with both an accessory and a duplicated MCA.

Takahashi *et al*.[160] proposed that the accessory MCA is a larger recurrent artery of Heubner (RaH), although this definition is no longer accepted[8, 11, 13, 137]. The RaH and the accessory middle cerebral artery often originate from the same segment; however, the RaH terminates in the anterior perforated substance, while the accessory MCA terminates as cortical branches[7]. Furthermore, the accessory MCA usually gives off perforators, whereas the RaH ends as a perforator[11, 13].

2.2.5.3. Fenestration

A fenestrated vessel has a common origin, splits into two channels and re-joins[46, 58, 92-94]. Fenestrations can be small slit-like or large convex-like[95, 161] and small slit-like fenestrations are most frequently observed[131, 162]. Fenestration of the MCA is usually observed in the M1 segments, although it can also be found in the M2 segment (Fig. 2.8K). Three types of M1 segment fenestrations can be defined; proximal, intermediate and the distal type (Fig. 2.8H, I and J). The proximal fenestration is the most common[41, 95, 101, 115, 148, 150, 163-168]. Fenestration of the MCA was observed in 0.1% to 5.8% (Table 2.7)[53, 58, 93, 107, 120, 122, 124, 125, 145, 148, 150, 161, 168] of cases. In previous studies the temporopolar artery commonly originates as an early temporal branch in association with fenestrations[46, 52, 93, 95, 115, 120, 150, 168, 169].

Table 1.7: The prevalence of fenestration, duplicated and accessory middle cerebral arteries[6, 32, 33, 36, 53, 55, 56, 58, 82, 93, 99, 105-107, 113, 114, 116, 118-125, 130, 131, 144-150, 154, 157, 158, 161, 168].

	Total	Duplicated MCA		Accessory MCA		Fenestration	
		Cases	%	Cases	%	Cases	%
Crompton (1962)	347	10	2.9%	1	0.3%	1	0.3%
Jain (1964)	300	2	0.7%	8	2.7%	-	-
Wollschlaeger *et al*. (1967)	582	-	-	-	-	1	0.2%
Ito *et al*. (1977)	1129	-	-	-	-	3	0.3%
Grellier *et al*. (1978)	280	1	0.4%	3	1.1%	-	-
Milenković (1981)	60	1	1.7%	-	-	-	-
Kayembe *et al*. (1984)	44	-	-	4	9.1%	-	-
Kayembe *et al*. (1984)	146	-	-	10	6.8%	-	-
Umansky *et al*. (1984)	70	-	-	2	2.9%	-	-
Atunes (1985)	37	-	-	-	-	1	2.7%
Kitami *et al*. (1985)	704	6	0.9%	4	0.6%	4	0.6%
Tran-Dinh (1986)	150	-	-	3	2.0%	-	-
Umansky *et al*. (1988)	104	1	1.0%	2	1.9%	1	1.0%
Yamamoto *et al*. (1992)	455	7	1.5%	14	3.1%	-	-
Sanders *et al*. (1993)	5190	-	-	-	-	9	0.2%
Meneses *et al*. (1997)	14	1	7.1%	1	7.1%	-	-
Ozaki *et al*. (1997)	153	2	1.6%	9	5.9%	-	-
Uchino *et al*. (2000)	425	9	2.1%	5	1.2%	2	0.5%
Gailloud *et al*. (2002)	1170	-	-	-	-	5	0.4%
Idowu *et al*. (2002)	100	-	-	1	1.0%	-	-
Tanriover *et al*. (2003)	50	1	2.0%	2	4.0%	-	-
Uchino *et al*. (2003)	900	14	1.6%	-	-	-	-
Karazincir *et al*. (2004)	176	1	0.6%	-	-	-	-
Tanriover *et al*. (2004)	43	-	-	2	4.7%	-	-
Kim *et al*. (2005)	448	2	0.4%	2	0.4%	2	0.4%
Kim *et al*. (2005)	743	6	0.8%	1	0.1%	1	0.1%
D'Ávila & Schneider (2006)	50	-	-	1	2.0%	-	-
Bharatha *et al*. (2008)	504	-	-	-	-	2	0.4%
Vuillier *et al*. (2008)	100	-	-	-	-	3	3.0%
Gielecki *et al*. (2009)	304	2	0.7%	-	-	-	-
Kim & Lee (2009)	1250	-	-	16	1.3%	-	-
van Rooij *et al*. (2009)	208	-	-	-	-	12	5.8%
Bayrak *et al*. (2011)	395	-	-	-	-	4	1.0%
Chang & Kim (2011)	1250	9	0.7%	-	-	-	-
Chang & Kim (2011)	1452	9	0.6%	-	-	-	-
Chang & Kim (2011)	2527	7	0.3%	-	-	-	-
Ogeng'o *et al*. (2011)	288	5	1.7%	-	-	-	-
Sun *et al*. (2012)	4652	-	-	-	-	3	0.06%
Uchino *et al*. (2012)	3491	-	-	-	-	3	0.09%
Hamidi *et al*. (2013)	500	7	1.4%	1	0.2%	10	2.0%
Cooke *et al*. (2014)	10927	-	-	-	-	10	0.09%
Kovač *et al*. (2014)	455	-	-	-	-	1	0.2%
van Rooij *et al*. (2015)	140	-	-	-	-	4	2.9%

Some authors observed an association between aneurysms and a duplicated MCA[143, 170, 171], although very few have observed aneurysms at the origin or near the abnormal vessel[136, 141, 172-176]. Selected authors[138, 139, 153, 155, 177-180] observed an association between aneurysms and an accessory MCA. Few studies[159, 181-188] have, however, reported aneurysms at the origin or near the vessel.

Fenestration might predispose patients to aneurysm formation[171] and certain authors have reported an association between aneurysms and fenestration (proximal or distal to the fenestration)[55, 98, 165, 171, 189-192]. Very few studies have, however, observed aneurysms at the site of the MCA fenestration[168, 193-195]. Furthermore, van Rooij *et al*.[161] stated that fenestrations with and without aneurysms were not statistically significantly different.

2.3. POSTERIOR CEREBRAL ARTERY

The posterior circulation is complex, tends to vary and very few studies have been conducted on the anatomy of the posterior cerebral artery (PCA)[9]. The PCA is the terminal branch of the basilar artery, originating anterior to the midbrain[11, 12]. There are four segments that can be described separately (Fig. 2.9). These include the P1 or precommunicating segment, the P2 or ambient segment, the P3 or quadrigeminal segment and the P4 or calcarine segment[12, 13, 196].

2.3.1. Segments

The proximal PCA refers to the P1 segment and the distal PCA refers to the part after the origin of the posterior communicating artery (PcoA). Very few studies focused on the anatomy of the PCA and the distal segment and cortical branches have particularly been neglected[197]. These segments are illustrated in Figure 2.9.

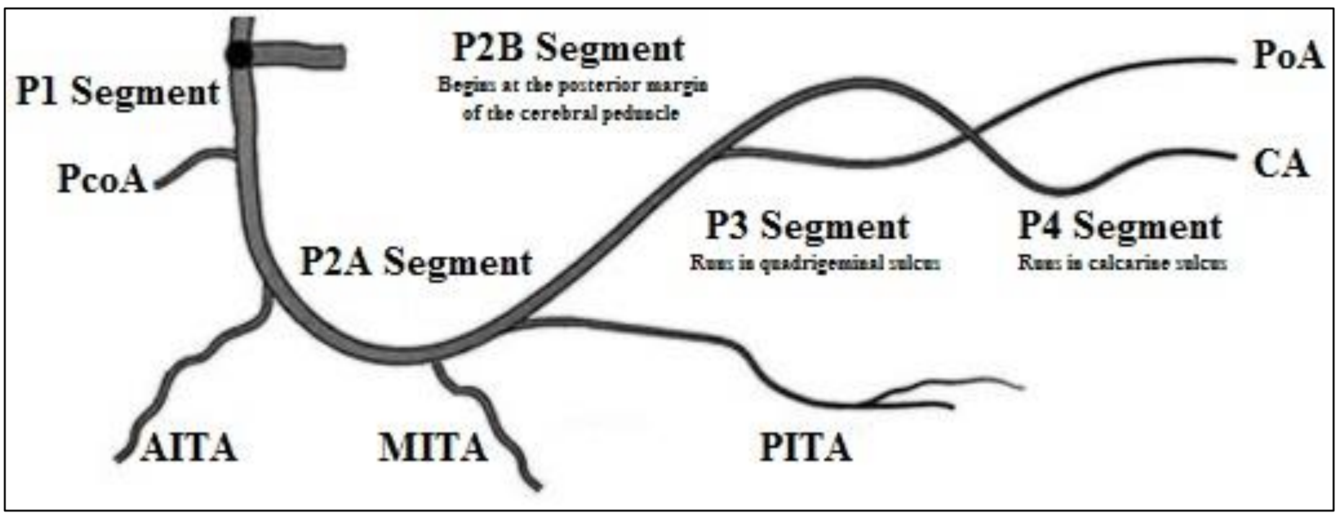

Figure 1.9: The different segments and cortical branches of the posterior cerebral artery (Adapted from Bradac[13]). (AITA) Anterior inferior temporal artery; (CA) Calcarine artery; (MITA) Middle inferior temporal artery; (PITA) Posterior inferior temporal artery; (PcoA) Posterior communicating artery; and (PoA) Parieto-occipital artery.

The P1 segment ends at the origin of the PcoA and the P2 segment extends from the junction of the PcoA to the posterior part of the midbrain[12]. The P2 segment can be subdivided into an anterior and posterior part, the P2A and P2P segments. The P2A segment extents from the PcoA and enters the proximal part of the ambient cistern. The P2P segment begins at the posterior margin of the cerebral peduncle[198-200]. Párraga *et al*.[201] stated that the most prominent, lateral aspect of the peduncle is an easier visualized point of division. The transition point between the P2A and P2P segments has also been described as the lateral mesencephalic sulcus[201].

The P3 segment is the continuation of the PCA within the perimesencephalic cistern. The P2 and P3 segment transition point has been described as the origin of the anterior inferior temporal artery (AITA), however, this point may vary[201]. The P3 segment often divides into terminal branches before ending at the calcarine fissure and the P4 segment originates at the anterior limit of the calcarine fissure[12, 199]. The parieto-occipital and calcarine arteries can run together for a short distance before bifurcating (early bifurcation)[201].

2.3.2. Cortical arteries

The PCA cortical branches include the anterior inferior temporal artery (AITA), middle inferior temporal artery (MITA), posterior inferior temporal artery (PITA), calcarine artery (CA), parieto-occipital artery (PoA) and in some cases a splenial artery (SA). These cortical branches can arise from the P2, P3 or P4 segments. The temporal arteries can also originate from a common trunk, the common temporal artery (CTA). These cortical branches can be absent, duplicated or triplicated[12, 199].

2.3.2.1. Temporal arteries

The temporal arteries (anterior, middle and posterior temporal arteries) can originate from the main trunk of the PCA, or from the common temporal artery. The CTA can also be referred to as the lateral occipital artery, the lateral division of the PCA or the temporo-occipital artery. This should not be confused with the MCA cortical branch, the temporo-occipital artery[12, 199, 202, 203]. The CTA usually originates from the P2 segment at the level of the lateral geniculate body[202].

The temporal arteries usually arise from the P2 segment (Table 2.8)[12, 146, 196, 199, 202]. Several authors[199, 202] have reported the MITA as the least consistent cortical branch of the PCA, and certain authors do not even describe this cortical branch[196]. Duplication of the PITA was present in 2.8% (one case)[202], 6.0% (three cases)[199] and 7.5% (three cases)[196] of specimens. Three or more posterior inferior temporal arteries have been observed in 12.5% (five cases)[196] in the literature.

Table 1.8: Origins of the temporal and common temporal arteries[199, 204].

	CTA		AITA		MITA		PITA	
Authors	Zeal & Rhoton (1978)	Haegelen *et al*. (2012)	Zeal & Rhoton (1978)	Haegelen *et al*. (2012)	Zeal & Rhoton (1978)	Haegelen *et al*. (2012)	Zeal & Rhoton (1978)	Haegelen *et al*. (2012)
Total	50	40	50	40	50	40	50	40
Presence	16.0%	20.0%	84.0%	80.0%	38.0%	20.0%	96.0%	80.0%
P2 segment:	-	-	-	-	-	-	-	-
P2A	37.5%	50.0%	76.2%	93.8%	42.1%	50.0%	4.2%	18.8%
Junction	-	12.5%	-	3.1%	-	12.5%	-	12.5%
P2P	62.5%	37.5%	23.8%	3.1%	57.9%	37.5%	89.6%	68.8%
P3 Segment	-	-	-	-	-	-	6.3%	-

(AITA) Anterior inferior temporal artery; (CTA) Common temporal artery; (MITA) Middle inferior temporal artery; and (PITA) Posterior inferior temporal artery.

The arteries that supply the temporal lobe were classified into five groups by Zeal and Rhoton[199]. The different groups are described in Table 2.9 and the frequencies observed by Zeal and Rhoton[199], Párraga *et al*.[201] and Haegelen *et al*.[204] are given.

Table 1.9: The prevalence of the temporal artery configurations[199, 201, 204].

	Description	Zeal & Rhoton (1978)	Párraga *et al.* (2011)	Haegelen *et al.* (2012)
Group 1	Present: AITA, MITA, PITA, hippocampal arteries	10.0%	36.0%	7.5%
Group 2	Present: CTA	16.0%	23.0%	20.0%
Group 3	Present: AITA, MITA, PITA Absent: hippocampal arteries	20.0%	8.0%	10.0%
Group 4	Present: AITA, PITA Absent: MITA, hippocampal arteries	10.0%	7.0%	47.5%
Group 5	Present: AITA, PITA, Hippocampal arteries Absent: MITA	44.0%	26.0%	15.0%

(AITA) Anterior inferior temporal artery; (CTA) Common temporal artery; (MITA) Middle inferior temporal artery; and (PITA) Posterior inferior temporal artery.

Haegelen *et al*.[204] proposed a new classification for the inferior temporal arteries of the PCA. In Type 1, anterior and posterior temporal arteries were present. In Type 2 the anterior hippocampal, anterior and posterior temporal arteries were present. In the Type 3 the common temporal artery was present. This was observed in 57.5%, 22.5% and 20.0% of cases, respectively[204].

2.3.2.2. Splenial artery

The SA supplies the splenium of the corpus callosum and can also be referred to as the posterior pericallosal artery[88, 199, 203]. The splenial artery usually arises from the parieto-occipital artery or the main stem of the PCA (Table 2.10)[203]. Duplication of the splenial artery can be observed and Türe *et al*.[88] stated that in 25.0% (10 cases), an accessory splenial artery was present. Zeal and Rhoton[199] observed the SA in all hemispheres; however, Margolis *et al*.[196] observed the SA in only 35.0% of 40 hemispheres. The SA can anastomose with branches of the pericallosal artery anterior to the splenium[199].

2.3.2.3. Terminal trunks

The parieto-occipital artery and the calcarine artery are the two terminal trunks of the PCA[12]. In a study by Zeal and Rhoton[199] on 50 hemispheres, the PoA was the terminal branch in 56.0% and in 44.0% the PCA terminated as the calcarine artery. The parieto-occipital and calcarine arteries supply the posterior third of the brain at the longitudinal fissure and part of the parietal and occipital lobes[12].

The origin of the calcarine artery is usually similar to the origin of the parieto-occipital artery since it usually arises from the same distal part of the PCA[202]. These cortical branches usually originate from the P3 segment (Table 2.10). Duplication of the calcarine artery was observed in 10.0% (five cases)[199], 20.0% (12 cases)[202] and 60.0% (24 cases)[196].

Table 1.10: Origins of the splenial, parieto-occipital and calcarine arteries[88, 196, 199, 201].

	SA			PoA			CA		
Authors	Zeal & Rhoton (1978)	Türe *et al*. (1996)	Párraga *et al*. (2011)	Margolis *et al*. (1971)	Zeal & Rhoton (1978)	Párraga *et al*. (2011)	Margolis *et al*. (1971)	Zeal & Rhoton (1978)	Párraga *et al*. (2011)
Total	50	40	70	40	50	70	40	50	70
Present:	100%	100%	90.0%	-	96.0%	100%	-	100%	91.4%
P2 segment:	-	2.0%	-	38.0%	-	-	16.0%	-	-
P2A	-	-	-	-	10.0%	-	-	-	-
P2P	4.0%	-	-	-	40.0%	1.4%	-	42.0%	-
P3 segments	4.0%	32.0%	30.2%	22.0%	-	71.4%	23.0%	48.0%	64.3%
P4 segments	-	-	3.2%	40.0%	-	27.1%	39.0%	-	27.1%
PoA	62.0%	52.0%	50.8%	-	-	-	16.0%	10.0%	8.6%
CA	12.0%	7.0%	-	-	-	-	-	-	-
PITA	6.0%	-	-	-	-	-	-	-	-
CTA	-	7.0%	-	-	-	-	-	-	-
MPChA/ LPChA	12.0%	-	15.9%	-	-	-	-	-	-

(CA) Calcarine artery; (CTA) Common temporal artery; (PITA) Posterior inferior temporal artery; (PoA) Parieto-occipital artery; and (SA) Splenial artery.

The parieto-occipital artery usually divides into a few different branches that either runs deep into the parieto-occipital fissure or the medial surface of the parieto-occipital lobe[196, 202, 203]. Duplication was observed in 1.7% (one case)[202] and 5.0% (one case)[196] in the literature.

2.3.2.4. Diameter and Lengths

The diameter and lengths of the PCA segments and cortical branches have not been thoroughly studied. The diameters and the length of the PCA segments, as reported in the literature[9, 200], are given in Table 2.11. There are limited reports on the diameter and length of the PCA cortical branches.

Table 1.11: The average diameter (mm) and length (mm) of the posterior cerebral artery segments[9, 200].

	Diameter Kawashima *et al*. (2005b)	**Length Pai *et al*. (2007)**	
		R	**L**
P2 Segment	-	19.9 mm (12-28 mm)	18.44 mm (10-28 mm)
P2A Segment	2.1 mm ± 0.4 mm	-	-
P2P Segment	1.7 mm ± 0.3 mm	-	-
P3 Segment	1.7 mm ± 0.2 mm	22.4 mm (13-38 mm)	20.9 mm (13-38 mm)

2.3.3. Branching pattern

The end of the main trunk has previously been described at the branching of the common temporal artery; however, the main trunk is now understood to end at the origin of the calcarine and parieto-occipital arteries. The level at which the main trunk terminates can differ. It typically divides at the P3 segment although the main trunk can run into the calcarine fissure and branch at the P4 segment. The main stem can be referred to as the medial occipital artery[205].

Three branching patterns of the distal PCA have been described by Milisavljević *et al*.[197]. In Type 1 the terminal division is at the P3 or P4 segment. In Type 2 the terminal division is at the P3 or P4 segment with the common temporal artery present. In Type 3 the terminal division is at the P2 segment (early branching). In 70 hemispheres, Milisavljević *et al*.[197] observed Type 1, Type 2 and Type 3 in 42.9%, 41.4%, and 15.7% of cases, respectively.

2.3.4. Anomalies

The cortical branches can either be absent, duplicated or triplicated. The origins of the arteries can exhibit typical variation; additionally, the cortical branches can also have abnormal origins. This includes the parieto-occipital, calcarine and posterior temporal arteries originating from the ICA[12]. Choi *et al*.[206] and Buxton and Cook[207] observed a rare case of the parieto-occipital artery originating from the ICA. Bergquist[208] observed a case of the PITA that originated from the internal carotid artery. True anomalies of the PCA include duplication, triplication and fenestration of the main stem of the PCA. The prevalence of the PCA anomalies are summarised in Table 2.12.

Table 1.12: The prevalence of the posterior cerebral artery anomalies[36, 53, 60, 62, 69, 99, 105, 107, 118, 146, 161, 197, 205, 209-213].

	Total	Fenestration		Duplication		Triplication	
		Cases	**%**	**Cases**	**%**	**Cases**	**%**
Windle (1888)	200	-	-	3	1.5%	-	-
Fisher (1965)	414	-	-	1	0.2%	-	-
Milenković (1981)	60	-	-	1	1.7%	-	-
Bartosiak *et al*. (1983)	50	-	-	1	2.0%	-	-
Bisaria (1984)	252	-	-	1	0.4%	-	-
Milisavljević *et al*. (1988)	70	1	1.4%	-	-	-	-
Caruso *et al*. (1991)	100	1	1.0%	1	1.0%	-	-
Karazincir *et al*. (2004)	176	1	0.6	-	-	-	-
Ladziński & Maliszewski (2005)	100	-	-	1	1.0%	-	-
Kapoor *et al*. (2008)	1000	-	-	23	2.3%	8	0.8%
van Rooij *et al*. (2009)	208	2	1.0%	-	-	-	-
Bayrak *et al*. (2011)	395	2	0.5%	-	-	-	-
Sun *et al*. (2012)	4652	1	0.02%	-	-	-	-
Hamidi *et al*. (2013)	500	7	1.4%	1	0.2%	-	-
Cooke *et al*. (2014)	10927	167	0.01%	-	-	-	-
Kovač *et al*. (2014)	455	-	-	1	0.2%	-	-
Gunnal *et al*. (2015)	340	3	0.9	5	1.5	-	-
Vlajković *et al*. (2015)	468	4	0.9%	-	-	-	-

2.3.4.1. Fenestration

Fenestration occurs when the lumen of an artery is divided into two segments. It can also be referred to as partial duplication. A fenestrated vessel has a common origin, splits into two channels and re-joins[46, 58, 92-94]. Fenestration of the PCA is extremely rare. The majority of these fenestrations are observed in the P1 segment; however, fenestrations can also be observed in either the P2 segment or the distal posterior cerebral artery[41, 45, 46, 107, 211, 214]. The mechanisms of the formation of PCA fenestrations are still unclear[45, 46]. Fenestrations in the posterior cerebral artery were observed in 0.01% to 1.4% (Table 2.12)[53, 99, 105, 107, 118, 161, 197, 211-213] of cases in previous studies. Most PCA fenestrations were reported as case studies[214 -218].

2.3.4.2. Duplicated and triplicated posterior cerebral arteries

The P1 and P2 segments can both be duplicated; however, the P1 segment is more commonly duplicated[211]. Kapoor *et al*.[62] reported that the additional branch originated from the P1 segment and ran mostly parallel to the main PCA. Kapoor *et al*.[62] describes duplication of the PCA as one branch arising from the PcoA and one from the basilar artery with a short junction between the two arteries. Early branching of the PCA was also described and this can present as duplication[208]. Duplication of the PCA was observed in 0.2% to 2.3% (Table 2.12)[36, 53, 60, 62, 69, 146, 205, 209-212] of cases. Most PCA duplications were reported as case studies[219, 220]. Duplication and triplication of the PCA are illustrated in Figure 2.10.

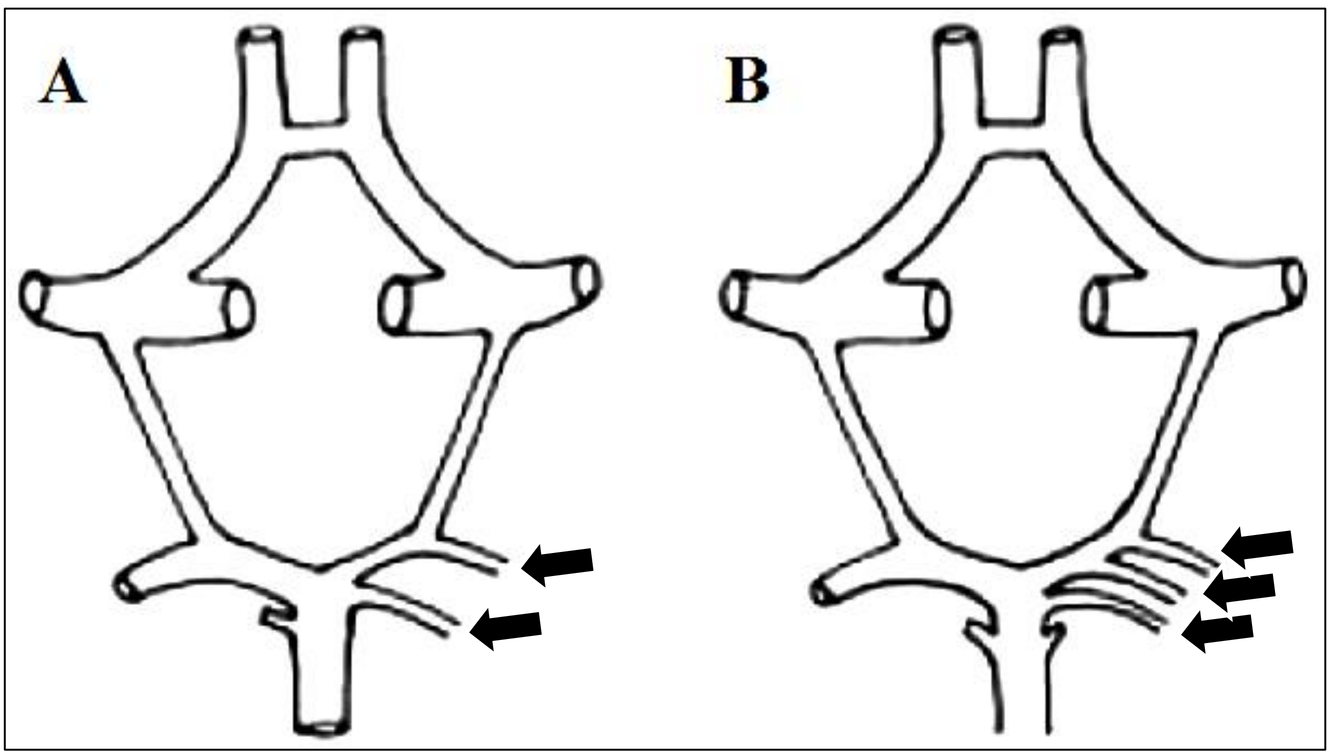

Figure 1.10: Anomalies of the posterior cerebral artery[62]. A) Duplication; and B) Triplication.

Few studies have reported triplication of the PCA. Kapoor *et al*.[62] observed triplication of the PCA in 0.8% (eight cases). Kapoor *et al*.[62] described three branches arising from the P1 segment that supplied the occipital and temporal lobes, although the middle branch tended to be very small.

CHAPTER THREE

PROBLEM STATEMENT, AIM, OBJECTIVES

3.1. PROBLEM STATEMENT

Possible differences in the diameter and length of the cerebral segments and cortical branches between age, population groups, sex and bilateral variation are, to the author's best knowledge, not mentioned or poorly reported in previous studies. Few studies give a complete description of the origins of the cortical arteries and reports on the diameter, length, absence, duplication and triplication are also limited. The MCA branching subtypes were mostly overlooked, only bifurcation and trifurcation is usually noted. The branching of the PCA has not been adequately described. The level of the PoA and CA origin is usually noted; however, whether branching is observed before the origin of these cortical branches is not mentioned. Anomalies of the cerebral arteries are usually only mentioned; few reports exist on the specific origin, length, diameter and cortical arteries that arise from these anomalous branches.

3.2. AIM

The aim of this study is to describe the anatomy and anomalies of the cerebral vasculature in a Southern African cadaver cohort.

3.3. OBJECTIVES

- To perfuse the anterior, middle and posterior cerebral arteries with a coloured silicone;
- To create digital images of the cerebral vasculature;
- To note origins, branching patterns and arterial variations;
- To measure the diameter and length of the vessels; and,
- To compare the results with the literature.

CHAPTER FOUR

MATERIALS AND METHODS

4.1. STUDY POPULATION

The National Health Act, No 61 of 2003 (sections 61 to 64)[221], states that human cadavers may be used for anatomical dissection and research in South Africa. Ethical clearance (S14/05/100) was obtained from the Health Research Ethics Committee (HREC) at Stellenbosch University. A pilot study was done on 10 specimens to ascertain the most effective method and agent for arterial perfusion. Embalmed cadavers (n=100) were used for the present study. According to the Death Certificates, the individuals died of causes unrelated to brain trauma since damage or lesions could influence the results. Previous studies[21, 78] excluded specimens that showed damage or brain trauma. Brains that were too degraded (due to an extended period between death and embalming) or damaged (during removal of brains), were excluded, resulting in 63 specimens suitable for use for the present study.

When only a section of the brain was damaged during removal, that specific cerebral artery was excluded. One-hundred hemispheres were used for the MCA, 121 hemispheres for the ACA and 124 hemispheres for the PCA. The total of 126 hemispheres consisted of males (n=88) and female (n=38) specimens between the ages of 22 and 84 (average 44 years of age). The specimens were distributed over three population groups, coloured (n=76), black (n=38), white (n=10) and unknown (n=2). This is tabulated in Table 4.1. Ten brains (20 hemispheres) were used for the pilot study, although, the ACA of one hemisphere was excluded due to damage during removal of the brain.

Table 4.1: Study population information.

		TOTAL	ACA	MCA	PCA
Total		126	121	100	124
Bilateral	Right	63	60	50	62
	Left	63	61	50	62
Sex	Male	88	83	68	86
	Female	38	38	32	38
Population Groups	Coloured	76	72	56	74
	Black	38	37	34	38
	White	10	10	8	10
	Unknown	2	2	2	2
Age Groups	<34	40	36	28	38
	35-48	36	35	29	36
	49>	40	40	33	40
	Unknown	10	10	10	10
	Minimum	22	22	22	22
	Maximum	84	75	75	84
	Average	44	45	45	45

(ACA) Anterior cerebral artery; (MCA) Middle cerebral artery; and (PCA) Posterior cerebral artery.

4.2. REMOVAL OF THE BRAIN

The scalp was reflected by making an incision from the nasion to the inion and from the vertex towards each ear bilaterally. The periosteum and temporalis muscle were reflected inferiorly. Using an oscillating bone saw (HEBU Medical, Oscillating Saw), the calvaria were cut from the supraorbital margin to the inion. The falx cerebri was separated from the crista galli and from the tentorium cerebelli. The optic, trochlear, abducent, trigeminal and oculomotor nerves were severed as well as the internal carotid arteries and pituitary stalk. The facial, hypoglossal, vagus, glossopharyngeal, accessory and vestibulocochlear nerves were then severed and the spinal cord was cut[222]. After removal of the brain, the specimens were placed in five litre buckets (containing 10% buffered formaldehyde) before perfusion of the cerebral arteries.

4.3. PREPARATION OF THE SPECIMENS

The arachnoid mater was removed to expose the Circle of Willis. The AcoA, posterior communicating arteries and the A1 segments (at the proximal origin) were clamped (indicated in green in Fig. 4.1). The

A1 segments were severed proximal to the origin of the AcoA and the P1 segments were cut before the origin of the PcoA (indicated in red in Fig. 4.1).

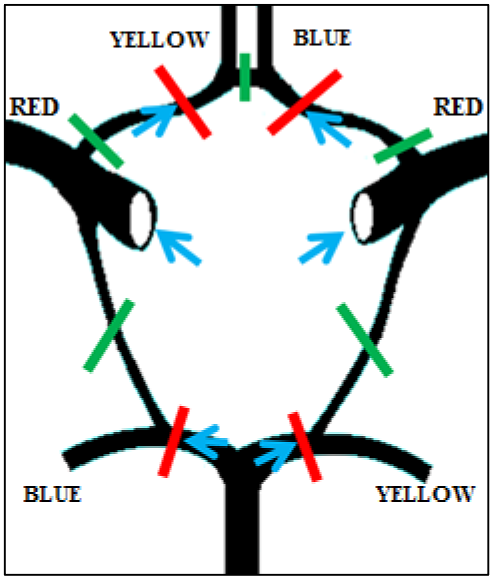

Figure 4.1: Perfusion of the cerebral arteries. Arrows indicate the position of insertion of the catheter, the red lines indicates the position where vessels were severed and the green lines indicate the sites of clamping.

The A1 segments, internal carotid arteries and P1 segments were cannulated with a plastic catheter (Vasofix® Safety 18 gage, B. Braun) (indicated as blue arrows in Fig. 4.1). An isotonic saline solution was injected (using a 1 mm syringe) into the arteries to remove any blood or blood clots[3, 21, 29, 57, 88, 200, 223, 224]. The arteries were then injected with coloured silicone (MM922 Silicone, ACC Silicone Concepts). The entire arterial system could be injected with the same colour, or the cerebral arteries could be cannulated separately[2]. Injecting the left and right anterior cerebral arteries with different colour allows visualization of any anastomoses between the two hemispheres[3]. In the current study each cerebral artery was injected with a different colour solution to assist in visualization of possible anastomoses between cerebral arteries.

Perfusion mediums used in similar studies include coloured silicone[16, 29, 30, 115, 200, 201], coloured latex or acrylic[2, 5, 6, 7, 14, 17, 28, 57, 78, 88, 121, 156, 157, 199, 204, 205, 225] and a mixture of India ink and gelatin[3, 7, 84, 200, 226]. In two studies[9, 127] the vessels were painted with water colour after dissection. Additional substances used include wax, varnish, coloured dyes, paint, barium sulphate, olive oil, Prussian blue, carmine, methyl methacrylate and acryplastic injection[121, 226, 227]. When pigment is added the smaller branches are easily identified and differentiated from the arachnoid strands[127].

After perfusion, the specimens were stored in 10% buffered formaldehyde solution for at least two weeks before the cerebral arteries were dissected. In previous studies, most authors used specimens that were fixed with formaldehyde[5, 10, 21, 22, 29, 32, 57, 67, 78, 87, 88, 91, 115, 157, 196, 199-201, 204, 205, 223, 225] although selected authors preferred to work with unfixed specimens[121, 228]. After completion of perfusion, digital images (using Canon IXUS 220 HS) were taken.

The ACA configuration was first examined at the interhemispheric region to observe any anastomoses between the two hemispheres. If there were any branches crossing from one hemisphere to the other, the anatomical details were recorded. The two hemispheres were then separated, with the use of a scalpel, at the corpus callosum to view the medial surface of the brain[3]. The temporal lobe was moved laterally to allow visualization of the middle cerebral artery[5]. Digital images were taken of the medial and lateral surface of each hemisphere.

4.4. MEASUREMENT OF THE VESSELS

The external diameter and length of all the cortical branches were measured using a digital micrometre. The diameter was measured at the origin of the branch and the lengths of the ACA cortical branches were measured from the origin of the branch to the AcoA[3, 16]. The length of the MCA cortical branches was measured from the origin of the middle cerebral artery to the origin of the branch, and the length of the PCA cortical branches was measured from the origin of the PCA to the origin of the branch.

Measurements by previous authors were made using digital callipers[16, 29, 78, 135], Vernier callipers[87], under magnification[6, 14, 28, 199, 229], ocular micrometre[223] and using the software “Image J”[230]. A calibrator and measuring tape have also been used[201].

4.5. STATISTICAL ANALYSIS

The diameter and length were measured three times, and a scatterplot was drawn to illustrate that there were no statistically significant differences between the measurements. The diameter and lengths of the cortical branches were compared using Mixed-effects REML regression. The statistical analysis was performed using the software, Statistica® Version 12.0 (StatSoft Inc. 2014, USA). A comparison was made between the left and right sides, sex, population groups and different age groups.

CHAPTER FIVE

RESULTS

5.1. PILOT STUDY: ANTERIOR CEREBRAL ARTERY

A pilot study (n=19) was done to assess the anatomy of the ACA and its branches. The most common variations were either complete absence or duplication of an artery. The diameter and length of the ACA cortical branches were measured. Any absence, duplications or triplications were reported and the origins of the branches were noted (Table 5.1).

The infra-orbital artery and the FpA were absent in eight cases (42.1%) and nine cases (47.4%), respectively, and the anterior, middle and posterior internal frontal arteries were always present. Furthermore, the AIFA and PIFA were duplicated in one case each. The MIFA was the most consistent artery; it was always present and never duplicated. The paracentral lobule artery was the most frequently duplicated (36.8%) vessel. The superior and inferior internal parietal arteries were absent in two cases (10.5%) and five cases (26.3%), respectively, and the IIPA was duplicated in one case. The callosomarginal artery and the IFA were both observed in only 31.6% of cases in the pilot study. Moreover, the callosomarginal artery and IFA were only present in the same hemisphere in one case. There were no triplicated cortical branches.

Table 5.1: The average diameter (mm), average length (mm), presence, duplication, triplication and origins of the anterior cerebral cortical branches observed in the pilot study.

	IfO	FpA	AIFA	MIFA	PIFA	IFA	PLA	SIPA	IIPA	CmA
Presence	57.9%	52.6%	100%	100%	100%	31.6%	100%	89.5%	73.7%	31.6%
Duplication	-	-	5.3%	-	5.3%	-	36.8%	-	5.3%	-
Triplication	-	-	-	-	-	-	-	-	-	-
Diameter	1.1	1.0	1.3	1.3	1.4	1.6	1.3	1.1	1.0	1.8
Length	9.8	21.0	28.3	46.9	53.2	34.6	81.0	99.9	90.9	33.1
A2 Segment	90.9%	40.0%	30.0%	-	-	16.7%	-	-	-	16.7%
A3 Segment	-	20.0%	40.0%	47.4%	45.0%	66.7%	3.8%	5.9%	-	83.3%
A4 Segment	-	-	-	-	10.0%	-	42.3%	17.6%	13.3%	-
A5 Segment	-	-	-	-	-	-	26.9%	64.7%	40.0%	-
CmA	-	-	10.0%	21.1%	25.0%	16.7%	15.4%	5.9%	-	-
IFA	9.1%	10.0%	20.0%	21.1%	15.0%	-	-	-	-	-
AIFA	-	30.0%	-	5.3%	-	-	-	-	-	-
MIFA	-	-	-	-	-	-	-	-	-	-
PIFA	-	-	-	5.3%	-	-	7.7% CT:3.8%	-	-	-
PLA	-	-	-	-	CT:5.0%	-	-	5.9%	-	-
SIPA	-	-	-	-	-	-	-	-	6.7%	-
PCA	-	-	-	-	-	-	-	-	40.0%	-

(AIFA) Anterior internal frontal artery; (CmA) Callosomarginal artery; (CT) Common trunk; (FpA) Frontopolar artery; (IFA) Internal frontal artery; (IfO) Infra-orbital artery; (IIPA) Inferior internal parietal artery; (MIFA) Middle internal frontal artery; (PIFA) Posterior internal frontal artery; (PLA) Paracentral lobule artery; (PoA) Posterior occipital artery; and (SIPA) Superior internal parietal artery.

The IfO and frontopolar artery most commonly arose from the A2 segment, while the IFA, frontal arteries and the CmA typically originated from the A3 segment. The paracentral lobule artery usually arose from the A4 segment, and the SIPA from the A5 segment. The IIPA arose equally from the A5 segment and posterior cerebral artery. The IIPA originated from the posterior cerebral artery in 40.0% of cases observed in the pilot study (Fig. 5.1); this was the most notable difference between the pilot study and what was reported in the literature.

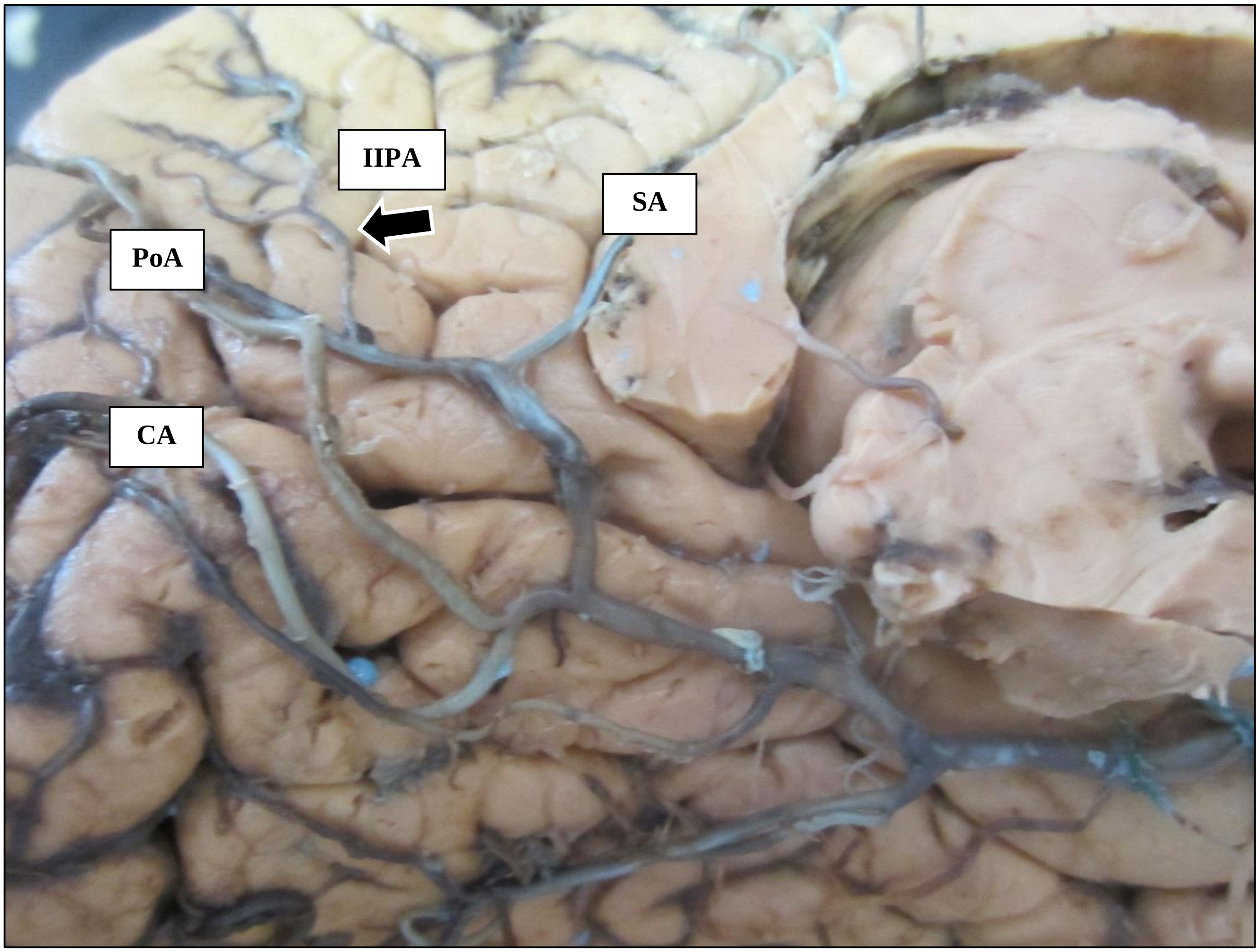

Figure 5.1: The inferior internal parietal artery originating from the posterior cerebral artery. (CA) Calcarine artery; (IIPA) Inferior internal parietal artery; (PITA) Posterior inferior temporal artery; (PoA) Parieto-occipital artery; and (SA) Splenial artery.

There were no azygos, bihemispheric or median anterior cerebral arteries observed in the pilot study, and fenestration was also not observed. This shows the need for larger studies on the anterior circulation.

5.2. PILOT STUDY: MIDDLE CEREBRAL ARTERY

A pilot study was conducted (n=20) to assess the anatomy of the MCA and its cortical branches. There were no cases with fenestrations, accessory or duplicated middle cerebral arteries. The branching pattern of the MCA was classified according to the 11 different types observed in the literature (Fig. 2.6). The exact distances used to classify the different branching patterns were, however, not noted in previous studies and had to be defined. Since early branching is classified as branching before 5 mm[117-120], medial and lateral branching were defined as branching between 5 mm and 20 mm, and branching after 20 mm, respectively. Bifurcation was observed in 16 cases, and these cases were further divided into medial bifurcation (50.0%), lateral bifurcation (25.0%) and lateral pseudobifurcation (5.0%). There were no cases of medial pseudobifurcation. True trifurcation and pseudotrifurcation were not observed, although two cases (10.0%) of proximal trifurcation and one case (5.0%) of distal trifurcation were observed. Some studies have failed to differentiate between true trifurcation and pseudotrifurcation; this distinction is, however, important to determine the true prevalence of these branching patterns. Tetrafurcation and pseudotetrafurcation were not observed, however, one case of monofurcation was present.

There is considerable variation in the MCA cortical branches in terms of size, number and area supplied[7]. The diameters and lengths of the different cortical branches are given in Table 5.2 as well as the percentage of duplicated branches. The most commonly duplicated branch was the anterior parietal artery in 30.0%. The most commonly absent cortical branch was the common temporal artery in 65.0% and the temporal polar artery in 40.0%. There were no triplicated cortical branches.

Table 5.2: The average diameter (mm), average length (mm), presence, duplication, triplication and origins of the middle cerebral cortical branches observed in the pilot study.

	OfA	PfA	PcA	CA	APA	PPA	AA	ToA	CTA	TpA	ATA	MTA	PTA
Presence	95.0	90.0	95.0	100	90.0	100	95.0	65.0	35.0	60.0	95.0	90.0	90.0
Duplication	15.0	5.0	25.0	25.0	30.0	15.0	5.0	-	-	-	-	-	5.0
Triplication	-	-	-	-	-	-	-	-	-	-	-	-	-
Diameter	1.4	1.5	1.3	1.4	1.4	1.5	1.5	1.5	1.5	1.1	1.2	1.1	1.4
Length	33.1	43.3	63.5	65.0	74.6	90.9	90.0	81.6	33.7	33.0	38.7	61.9	66.0
EB	23.8%	22.2%	-	-	-	-	-	-	16.7%	54.5%	27.8%	-	16.7%
INF	-	-	-	4.3%	17.4%	40.9%	78.9%	91.7%	66.7%	27.3%	50.0%	47.1%	61.1%
SUP	47.6%	77.8%	95.7%	91.3%	78.3%	50.0%	21.1%	8.3%	-	-	-	-	-
CTA	-	-	-	-	-	-	-	-	-	18.2%	22.2%	29.4%	11.1%
PfA	28.6%	-	-	-	-	-	-	-	-	-	-	-	-
PcA	-	-	-	4.3%	-	-	-	-	-	-	-	-	-
CA	-	-	4.3%	-	4.3%	-	-	-	-	-	-	-	-
AA	-	-	-	-	-	9.1%	-	-	-	-	-	-	-
ToA	-	-	-	-	-	-	-	-	-	-	-	5.9%	11.1%
PTA	-	-	-	-	-	-	-	-	16.7%	-	-	17.6%	-

Monofurcation was excluded for origins.
(AA) Angular artery; (APA) Anterior parietal artery; (ATA) Anterior temporal artery; (CA) Central artery; (EB) Early branches; (INF) Inferior trunk; (MTA) Middle temporal artery; (OfA) Orbitofrontal artery; (PcA) Precentral artery; (PfA) Prefrontal artery; (PPA) Posterior parietal artery; (PTA) Posterior temporal artery; (ToA) Temporo-occipital artery; (TpA) Temporopolar artery; and (SUP) Superior trunk.

Very few studies describe the origins of the cortical MCA branches, therefore the origins of the cortical branches were noted in the pilot study and a detailed description is given in Table 5.2. The temporal and temporo-occipital arteries usually originated from the inferior trunk, and the OfA, PfA, precentral and central arteries typically originated from the superior trunk. The parietal arteries and angular artery originated from either the superior or the inferior trunk.

Early frontal branches that were commonly observed included the OfA in 23.8% and the prefrontal artery in 27.8% of cases. The TpA was most commonly observed as an early temporal branch in 54.5% of cases. Common trunks between arteries occurred frequently. The PfA and precentral artery originated as a common trunk in 42.1%, the temporopolar artery and ATA originated with a common trunk in 31.6%, and the PcA and central artery in 31.6% of cases.

5.3. PILOT STUDY: POSTERIOR CEREBRAL ARTERY

Twenty hemispheres were perfused with coloured silicone to assess the anatomy of the PCA. The diameter and length of the PCA cortical branches were measured. Any absence, duplications or triplications were reported and the origins of the branches were noted (Table 5.3). The most common variations were either complete absence or duplication of an artery. The most frequently absent arteries were the splenial artery in 16 cases (80.0%) and the common temporal artery in 14 cases (70.0%). Most commonly duplicated was the calcarine artery in 25.0% (five cases) and the AITA was the only triplicated artery (one case).

The P2A segment usually gave origin to the temporal arteries (anterior, middle and posterior inferior temporal arteries) and the common temporal artery. The calcarine artery and PoA usually originated from the P3 segment and the splenial artery usually originated from the parieto-occipital artery (50.0%). The common temporal artery was present in only six cases; in three cases it gave origin to the MITA and PITA, and in three cases it gave origin to all three temporal arteries. A complete description is given in Table 5.3.

Table 5.3: The average diameter (mm), average length (mm), presence, duplication, triplication and origins of the posterior cerebral cortical branches observed in the pilot study.

	CTA	AITA	MITA	PITA	CA	PoA	SA
Presence	30.0%	75.0%	95.0%	95.0%	100%	100%	20.0%
Duplication	-	10.0%	-	10.0%	25.0%	10.0%	-
Triplication	-	5.0%	-	-	-	-	-
Diameter	2.0	1.0	1.3	1.6	1.2	1.5	0.8
Length	25.7	19.5	27.0	30.8	52.0	55.4	63.2
P2A	100%	77.8%	47.4%	52.4%	16.0%	13.6%	-
P2P	-	-	-	4.8%	24.0%	18.2%	25.0%
P3	-	-	-	4.8%	44.0%	54.6%	-
P4	-	-	-	-	8.0%	9.1%	-
CTA	-	11.1%	31.6%	28.6%	-	-	-
MITA	-	-	-	4.8%	-	-	-
PITA	-	11.1%	21.1%	-	4.0%	-	25.0%
CA	-	-	-	4.8%	-	4.6%	-
PoA	-	-	-	-	4.0%	-	50.0%

(AITA) Anterior inferior temporal artery; (CA) Calcarine artery; (CTA) Common temporal artery; (MITA) Middle inferior temporal artery; (PITA) Posterior inferior temporal artery; (PoA) Parieto-occipital artery; and (SA) Splenial artery.

Anomalies of the PCA are uncommon; however a large fenestration was observed in the left P2A segment in one case in the pilot study. This is illustrated in Figure 5.2. There were no cases of duplication or triplication of the posterior cerebral artery.

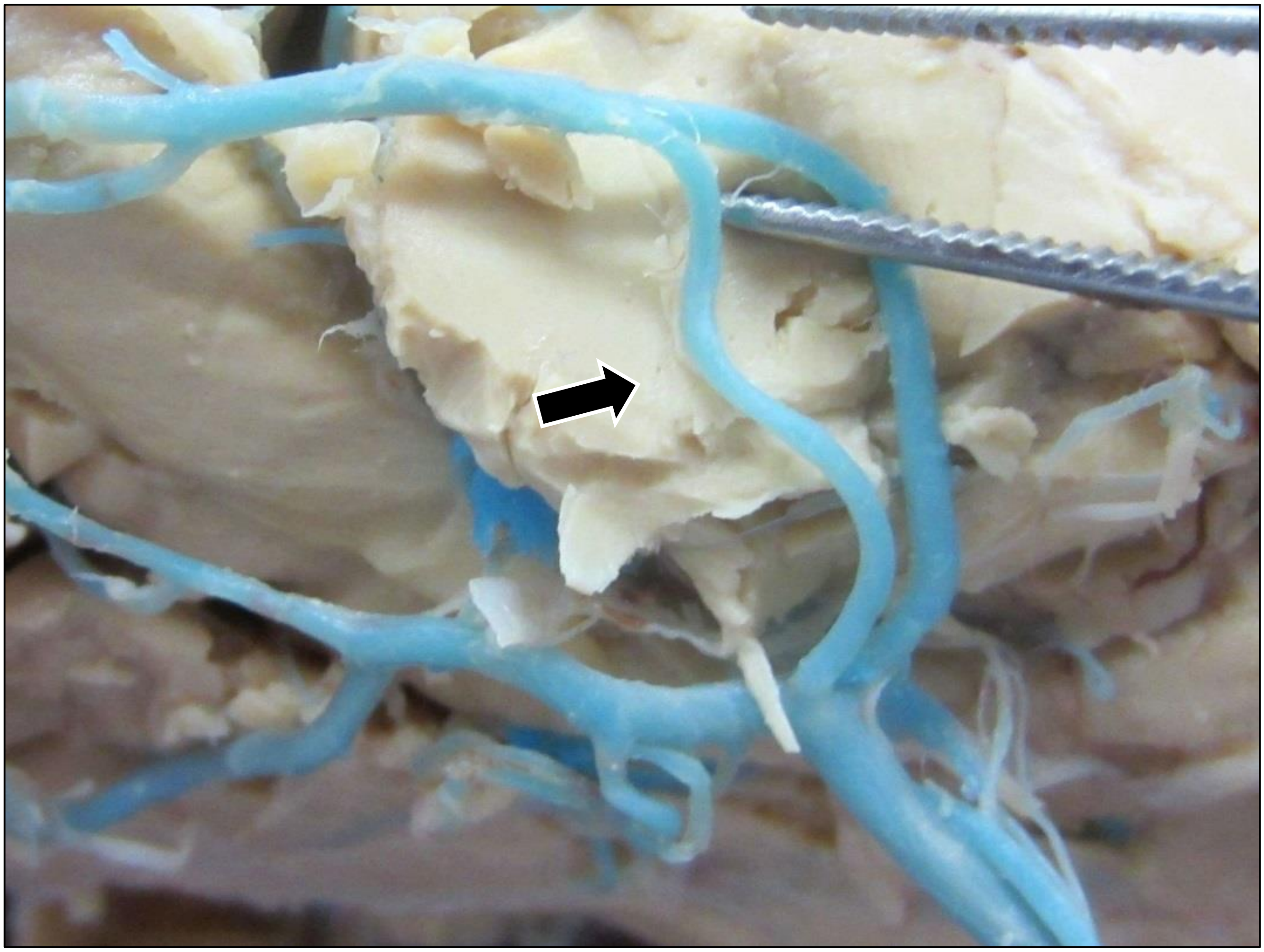

Figure 5.2: Fenestration of the P2A segment.

The branching pattern of the PCA was assessed, since the literature does not give a sufficient description on this subject. Monofurcation, bifurcation and trifurcation was described and these different branching types are illustrated in the line diagram in Figure 5.3.

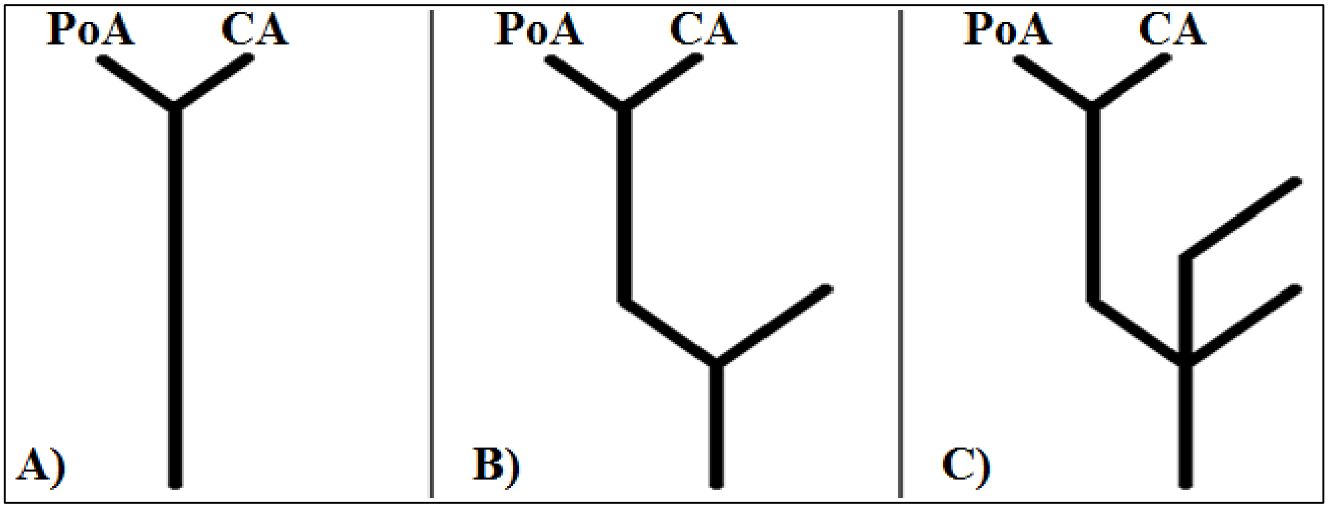

Figure 5.3: The different branching types of the posterior cerebral artery. A) Monofurcation; B) Bifurcation; and C) Trifurcation. (CA) Calcarine artery; and (PoA) Parieto-occipital artery.

The literature states that the main branching of the PCA is at the division between the PoA and the calcarine artery (end of the main trunk). In the 20 hemispheres that were assessed, this pattern was only observed in one hemisphere. This branching type was referred to as “monofurcation” of the PCA (Fig. 5.3A).

In the other cases there was an additional branching before the division of the calcarine artery and PoA, resulting in two similar sized trunks. This branching type was referred to as “bifurcation” of the PCA (Fig. 5.3B). This bifurcation was observed at the origin of the CTA in six cases. When the common temporal artery was absent, this bifurcation was located at the origin of the PITA in eight cases, and at the origin of the MITA in two cases.

A “trifurcation” branching type (Fig. 5.3C) was observed in the remaining three hemispheres. The first case was due to fenestration of the P2A segment (Fig. 5.3). In the second case there was early branching of the parieto-occipital and calcarine artery with the MITA arising at the bifurcation. In the remaining case the anterior and posterior inferior temporal arteries arose at the same origin, resulting in trifurcation.

5.4. PRESENT STUDY: ANTERIOR CEREBRAL ARTERY

In the present study a total of 121 hemispheres were studied to assess the anatomy of the ACA, including 60 right, and 61 left hemispheres. The segments, cortical branches and anomalies of the ACA are described separately.

5.4.1. Segments

The diameter and length of the segments of the ACA were measured and is tabulated in Table 5.4. A comparison is made between the left and right sides, sex, population groups and different age groups. Few studies comment on these parameters.

There were statistically significant differences between the right and left A3 segment diameter and length. There was also a statistically significant difference between the right and left A4 segment length. The only statistically significant difference between males and females were in the A3 segment length (females had a shorter A3 segment). The only statistically significant difference between population groups were between Group 1 (specimens from the coloured population group) versus Group 3 (specimens from the white population group) for the A3 segment diameter (specimens from the white population group had a larger diameter). There were no statistically significant differences observed between the different age groups for the diameter and length of the A2, A3 and A4 segments. The statistically significant differences are indicated in the table (Table 5.4).

Table 5.4: The average diameter (mm) and length (mm) of the A2, A3 and A4 segments observed bilaterally, between males and females, different population groups and different age groups.

Segment		Average	Bilateral		Sex		Population Groups			Age Groups		
			Right	Left	Male	Female	Group 1: Coloured	Group 2: Black	Group 3: White	Group 1: 22-34	Group 2: 35-48	Group 3: 49-75
A2	**D**	2.3	2.3	2.4	2.4	2.3	2.3	2.4	**2.7**[B]	2.3	2.4	2.4
	L	19.2	19.1	19.5	19.6	18.5	19.9	18.7	**16.9**[B]	19.2	19.5	18.8
A3	**D**	2.1	**2.0***	**2.2***	2.1	2.1	2.0	2.1	2.4	2.0	2.1	2.1
	L	36.3	**37.2***	**35.7***	**37.4***	**34.2***	35.5	37.1	41.5	35.7	35.4	38.3
A4	**D**	1.6	1.6	1.7	1.7	1.6	1.7	1.6	1.6	1.6	1.7	1.6
	L	25.4	**26.1***	**24.5***	25.8	24.0	25.2	26.3	23.0	24.9	26.4	24.7

(D) Diameter; (L) Length
(*) Indicates a statistically significant difference ($p < 0.05$)
([B]) Indicates a statistically significant difference ($p < 0.05$) between Group 1 and Group 3

5.4.2. Cortical Branches

The diameter and length of the ACA cortical branches were measured. Any absence, duplications or triplications were reported and the origins of the branches were noted.

5.4.2.1. Diameter and Length

The diameter and length of the different ACA cortical arteries are tabulated in Table 5.5. A comparison is made between the left and right sides, sex, population groups and different age groups. Very few studies commented on these parameters. The cortical branch with the greatest diameter was the callosomarginal artery. The smallest arteries were the IfO and FpA (0.9 mm). The IfO also had the shortest length (18.8 mm) and the parietal arteries had the longest length.

There were statistically significant differences between the length of the FpA, the anterior, middle and posterior internal frontal arteries on the right and left side (left side usually larger). The diameter of the FpA and internal frontal artery was bilaterally (between left and right) statistically significantly different. The only statistically significant difference between males and females was the PLA length (longer in males). There was no statistically significant difference between the different population groups. A statistically significant difference was observed between different age groups in PIFA and PLA diameter. The older groups (Group 2 and Group 3) had larger diameters compared to the younger group (Group 1). The IFA length was statistically significantly different between age Group 1 and Group 3 (older age group had a longer length). The statistically significant differences are indicated in the table (Table 5.5).

Table 5.5: The average diameter (mm) and length (mm) of the anterior cerebral cortical branches observed bilaterally, between males and females, different population groups and different age groups.

Cortical Arteries		Average	Bilateral		Sex		Population Groups			Age Groups		
			Right	Left	Male	Female	Group 1: Coloured	Group 2: Black	Group 3: White	Group 1: 22-34	Group 2: 35-48	Group 3: 49-75
IfO	**D**	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.9	0.9	0.9
	L	18.8	19.0	17.7	18.6	18.0	19.7	14.6	22.0	22.1	15.0	16.5
FpA	**D**	0.9	**0.9***	**1.0***	1.0	0.9	0.9	0.9	1.1	0.9	1.0	1.0
	L	20.1	**22.4***	**17.6***	19.2	22.1	21.8	16.9	14.5	19.5	19.5	20.8
IFA	**D**	1.5	**1.5***	**1.6***	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.6
	L	27.4	28.6	26.0	27.2	27.4	27.6	26.2	28.5	20.9	23.4	**34.0[B]**
AIFA	**D**	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.2	1.0	1.1	1.1
	L	28.6	**30.9***	**25.8***	27.8	30.2	28.7	28.2	26.3	27.9	28.4	28.4
MIFA	**D**	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.1	1.2	1.2
	L	41.1	**43.3***	**38.6***	41.8	39.0	41.5	38.4	45.9	43.5	37.1	42.8
PIFA	**D**	1.3	1.3	1.3	1.3	1.2	1.3	1.2	1.5	1.1	**1.4[A]**	**1.4[B]**
	L	52.8	**55.4***	**50.2***	54.1	49.9	53.1	51.8	54.2	52.3	52.5	53.5
PLA	**D**	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.4	1.2	**1.4[A]**	**1.3[B]**
	L	71.9	73.6	69.4	**74.3***	**64.8***	70.7	72.4	74.8	69.2	71.1	73.7
SIPA	**D**	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.1	1.2	1.2
	L	81.3	83.0	79.7	82.6	78.3	83.0	78.5	75.5	79.3	78.2	85.3
IIPA	**D**	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	1.0	1.0	1.0
	L	81.5	83.4	79.9	82.8	77.4	80.7	82.4	78.0	80.1	81.9	80.5
CmA	**D**	2.0	2.0	2.1	2.0	1.9	1.9	2.0	-	2.0	1.8	2.0
	L	21.6	19.3	25.1	21.7	21.3	24.1	21.4	-	20.8	21.1	30.0

(AIFA) Anterior internal frontal artery; (CmA) Callosomarginal artery; (D) Diameter; (FpA) Frontopolar artery; (IFA) Internal frontal artery; (IfO) Infra-orbital artery; (IIPA) Inferior internal parietal artery; (L) Length; (MIFA) Middle internal frontal artery; (PIFA) Posterior internal frontal artery; (PLA) Paracentral lobule artery; and (SIPA) Superior internal parietal artery.

(*) Indicates a statistically significant difference ($p < 0.05$)

([A]) Indicates a statistically significant difference ($p < 0.05$) between Group 1 and Group 2

([B]) Indicates a statistically significant difference ($p < 0.05$) between Group 1 and Group 3

5.4.2.2. Absence, duplication and triplication

The most variable artery was the CmA, since it was present in only 15 cases (12.4%). The PLA is referred to as the most consistent artery (always present), and was perceived in the present study as well. Most frequently absent was the CmA and the IFA in 87.6% and 70.2% of cases, respectively. In the literature the presence of these arteries are described as inconstant. There were only two arteries that were never absent, the PIFA and the paracentral lobule artery. The most commonly duplicated artery was the paracentral lobule artery in 31.4% of cases. The infra-orbital artery, frontopolar artery, IFA and callosomarginal arteries were never duplicated. There were only two triplicated arteries, the paracentral lobule artery in one case (0.8%), and the IIPA in one case (0.8%).

5.4.2.3. Origins

The origins of the ACA cortical branches are tabulated in Table 5.6. The most common origins of the cortical branches are illustrated in Figure 5.4, although it should be mentioned that this specific configuration was not observed in the present study.

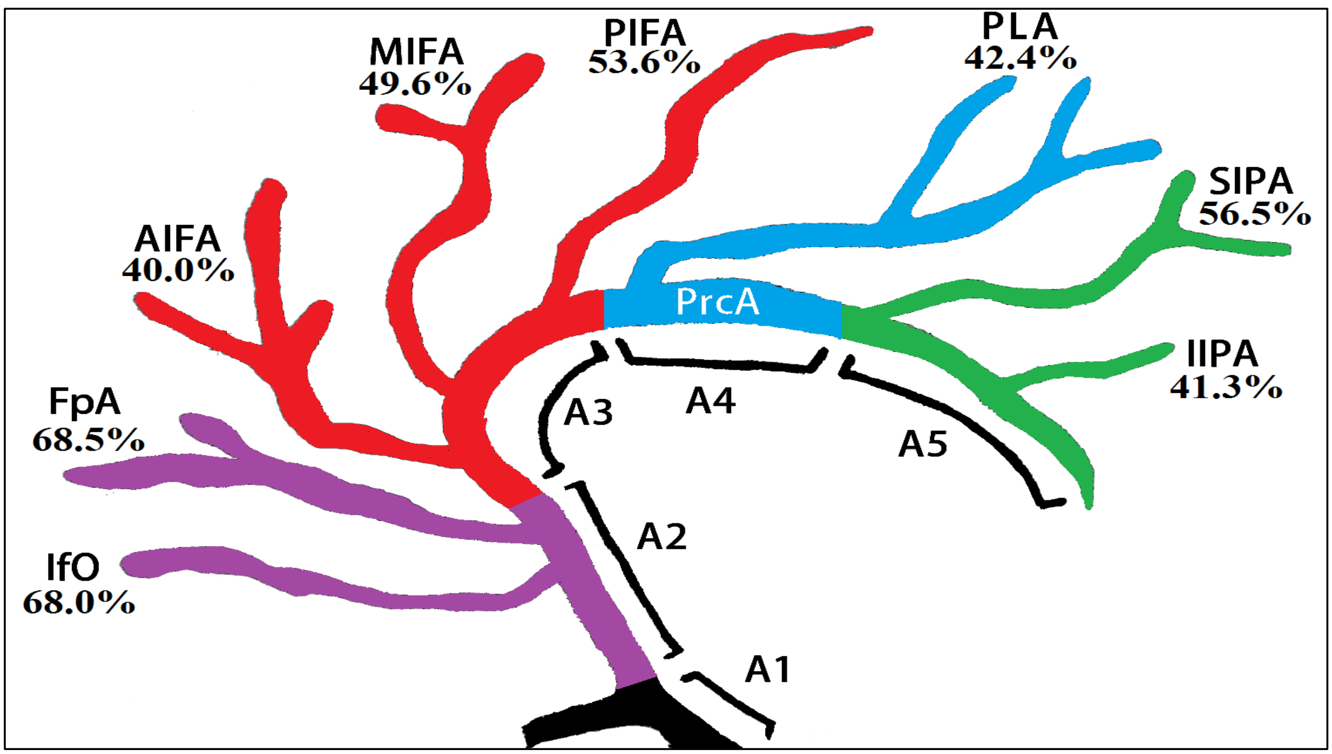

Figure 5.4: The most common origins of the anterior cerebral cortical branches.
(AIFA) Anterior internal frontal artery; (FpA) Frontopolar artery; (IfO) Infra-orbital artery; (IIPA) Inferior internal parietal artery; (MIFA) Middle internal frontal artery; (PLA) Paracentral lobule artery; (PIFA) Posterior internal frontal artery; (PrcA) Pericallosal artery; and (SIPA) Superior internal parietal artery.

Table 5.6: The presence, duplication, triplication and origin of the anterior cerebral cortical branches observed in the present study.

	IfO	FpA	AIFA	MIFA	PIFA	IFA	PLA	SIPA	IIPA	CmA
Presence	41.3%	60.3%	97.5%	99.2%	100%	29.8%	100%	97.5%	69.4%	12.4%
Duplicated	-	-	5.8%	12.4%	15.7%	-	31.4%	5.0%	5.8%	-
Triplicated	-	-	-	-	-	-	0.8%	-	0.8%	-
A1 Segment	2.0%	-	0.8%	-	-	-	-	-	-	-
A2 Segment	68.0%	68.5%	28.8%	5.2%	-	22.2%	-	0.8%	-	33.3%
A3 Segment	2.0%	8.2%	40.0%	49.6%	53.6%	69.4%	16.8%	8.1%	2.2%	60.0%
A4 Segment	-	-	-	-	15.7%	-	42.4%	26.6%	6.5%	-
A5 Segment	-	-	-	-	-	-	24.8%	56.5%	41.3%	-
CmA	2.0%	4.1%	4.8%	10.4%	12.9%	8.3%	8.7%	-	-	-
IFA	2.0%	4.1%	16.0%	27.4%	15.0%	-	-	-	-	-
MedACA	-	-	-	0.7%	0.7%	-	3.7%	7.3%	3.3%	-
AcoA	-	-	-	-	-	-	-	-	-	6.7%
FpA	12.0%	-	-	-	-	-	-	-	-	-
AIFA	12.0%	11.0%	-	1.5%	-	-	-	-	-	-
MIFA	-	4.1%	9.6%	-	-	-	-	-	-	-
PIFA	-	-	-	5.2%	-	-	3.1%	-	-	-
PLA	-	-	-	-	1.4%	-	-	0.8%	-	-
SIPA	-	-	-	-	-	-	0.6%	-	2.2%	-
PCA	-	-	-	-	0.7%	-	-	-	44.6%	-

(AcoA) Anterior communicating artery; (AIFA) Anterior internal frontal artery; (CmA) Callosomarginal artery; (FpA) Frontopolar artery; (IFA) Internal frontal artery; (IfO) Infra-orbital artery; (IIPA) Inferior internal parietal artery; (MedACA) Median anterior cerebral artery; (MIFA) Middle internal frontal artery; (PCA) Posterior cerebral artery; (PIFA) Posterior internal frontal artery; (PLA) Paracentral lobule artery; (PoA) Parieto-occipital artery; and (SIPA) Superior internal parietal artery.

The IfO and frontopolar artery mostly originated from the A2 segment in 68.0% and 68.5% of cases, respectively. The CmA, anterior, middle and posterior internal frontal arteries, and the IFA usually originated from the A3 segment. The paracentral lobule artery typically originated from the A4 segment and the SIPA from the A5 segment. The IIPA originated almost equally from the PCA and A5 segment in 44.6% and 41.3%, respectively.

Uncommon origins included the IfO arising from the AIFA and FpA in 12.0% each, and the FpA arose from the AIFA in 11.0% and from the MIFA in 9.6% of cases. The SIPA originated from the A2 segment in one cases. This was due to the CmA that was present and gave origin to all the cortical branches except the SIPA (the IIPA was absent).

The IfO and FpA commonly arose as common trunks in 11 cases. These common trunks originated from the A2 segment (seven cases), AIFA (two cases), A3 segment (one case) and the callosomarginal artery (one case). The frontopolar artery and AIFA arose as a common trunk in ten cases. These common trunks originated from the A2 segment (eight cases), A3 segment (one case) and CmA (one case). In one case the infra-orbital artery and AIFA originated from a common trunk from the A1 segment.

(i) Callosomarginal artery

The CmA was observed in only 15 cases (all typical configuration). The callosomarginal artery originated from the AcoA in one case (6.7%), from the A2 segment in 33.3% and from the A3 segment in 60.0% of cases in the present study. Furthermore, the CmA gave origin to the following subgroups (Fig. 5.5): the middle and posterior internal frontal arteries and PLA (46.7%), the anterior, middle and posterior internal frontal arteries and the PLA (20.0%), the IFA, posterior internal frontal artery and PLA (20.0%), the frontal arteries and paracentral lobule and the FpA (6.7%), and the anterior and middle internal frontal arteries, IfO and frontopolar artery.

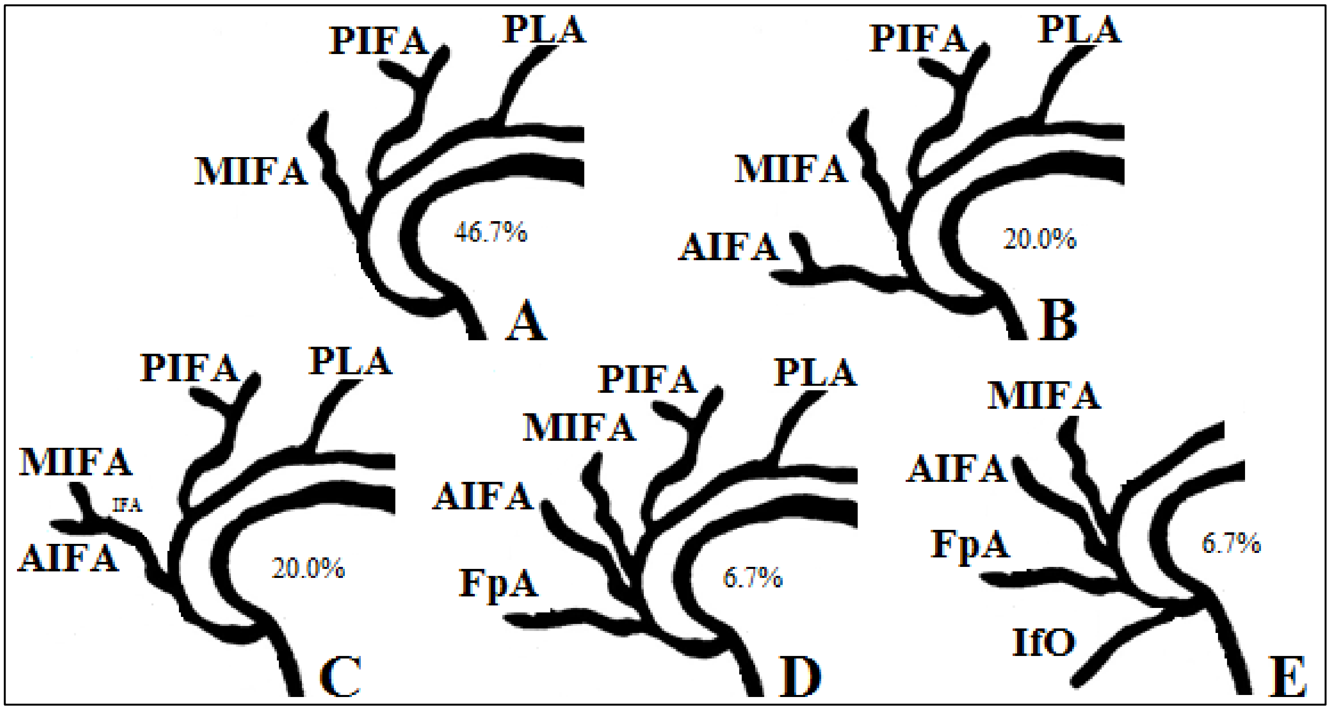

Figure 5.5: The different configurations of the callosomarginal artery. (AIFA) Anterior internal frontal artery; (FpA) Frontopolar artery; (IfO) Infra-orbital artery; (MIFA) Middle internal frontal artery; (PLA) Paracentral lobule artery; and (PIFA) Posterior internal frontal artery.

(ii) Frontal arteries

The frontal arteries can originate from a common trunk, referred to as the internal frontal artery. The IFA was present in 36 cases (29.8%) in the present study. The IFA gave origin to the anterior and middle internal frontal arteries in 41.7%, to the middle and posterior internal frontal arteries in 44.4%, and to all three frontal arteries in 13.9% of cases observed. These different configurations are illustrated in Figure 5.6.

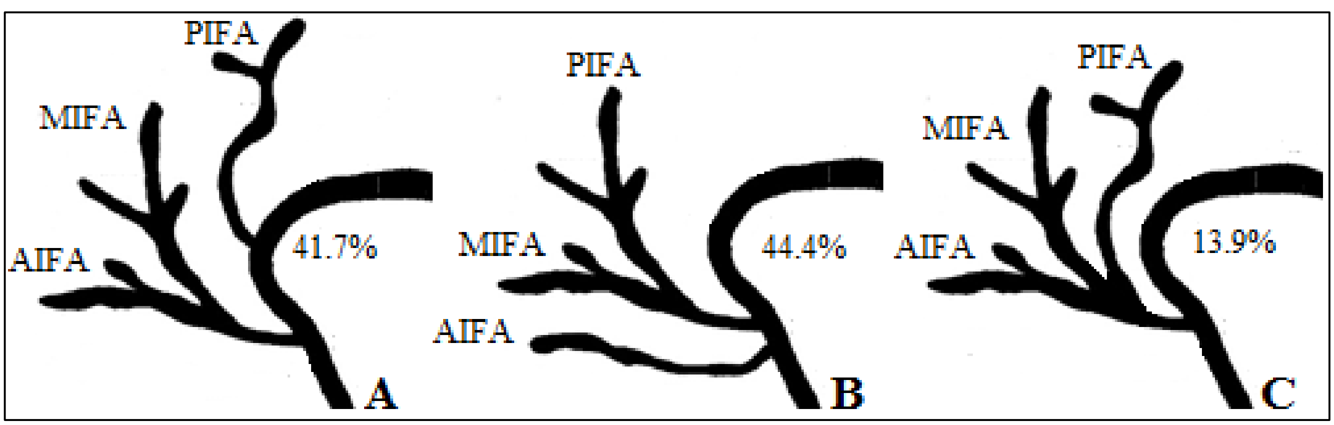

Figure 5.6: The different configurations of the internal frontal artery. (AIFA) Anterior internal frontal artery; (MIFA) Middle internal frontal artery; and (PIFA) Posterior internal frontal artery.

The diameter of the IFA was the smallest when giving origin to the anterior and middle internal frontal arteries (1.4 mm) and largest when supplying all three frontal arteries (1.7 mm). The diameter was, however, largest when the IFA originated from the A3 segment (1.6 mm).

5.4.3. Anomalies

The azygos ACA was not observed and no ACA fenestrations were observed in the present study. There were seven cases (11.6%) of a median ACA (Fig. 5.7 and Fig. 5.8) and 12 cases (19.8%) of a bihemispheric ACA observed in the present study (Fig. 5.9 and Fig. 5.10). Insufficient details regarding the median and bihemispheric anterior cerebral arteries are given in the literature and these anomalies are usually only mentioned. Little or no description is given on which branches are given off by these abnormal arteries, or between which cortical arteries the bihemispheric branch arises.

5.4.3.1. Median anterior cerebral artery

The median ACA was observed in seven specimens and a line diagram of each case is given in Figure 5.7. The area supplied by the bihemispheric branch is indicated in green. The MedACA originated mostly from the AcoA in 85.7% (six cases) and from the A2 segment in 14.3% (one case). Two subgroups can be described, unilateral and bilateral MedACA.

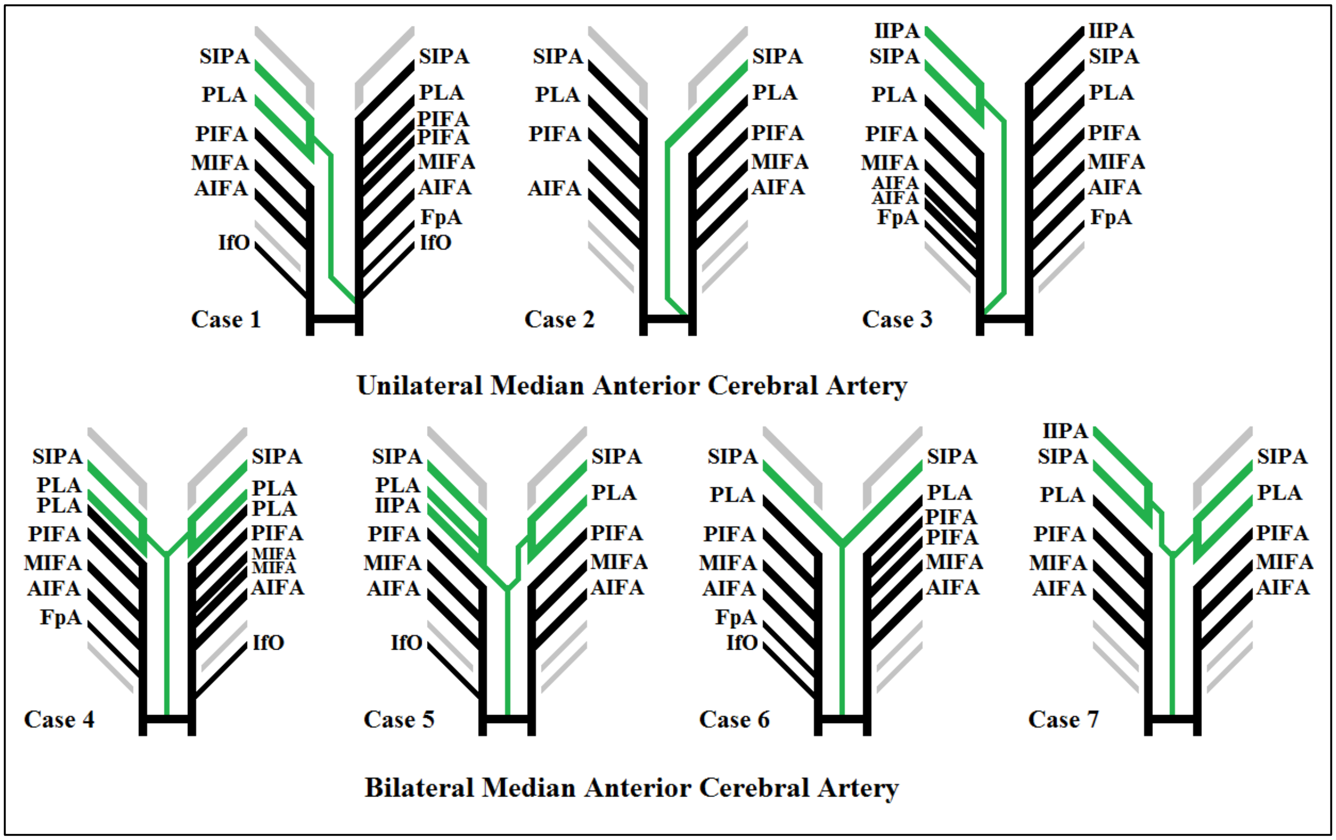

Figure 5.7: The median anterior cerebral arteries observed in the present study.
(AIFA) Anterior internal frontal artery; (FpA) Frontopolar artery; (IfO) Infra-orbital artery; (IIPA) Inferior internal parietal artery; (MIFA) Middle internal frontal artery; (PLA) Paracentral lobule artery; (PIFA) Posterior internal frontal artery; and (SIPA) Superior internal parietal artery.

The median ACA supplied both hemispheres in four cases (bilateral median ACA) and only one hemisphere in three cases (unilateral median ACA). The only arteries that arose from the MedACA were the SIPA (most common), IIPA and paracentral lobule artery. The SIPA always originated from the MedACA when present and in cases where both hemispheres where supplied by the MedACA, the superior internal parietal artery arose from the MedACA to supply both hemispheres. The paracentral lobule artery was present in six of the seven cases and the IIPA in only three cases.

(i) Unilateral median anterior cerebral artery

In the first case, the median ACA arose from the left A2 segment, although the MedACA only gave origin to branches on the right (SIPA and paracentral lobule artery). In the second case, the MedACA only gave rise to the SIPA. This case can be viewed as an anomalous origin of the SIPA from the AcoA. In the third case, the median ACA only gave origin to the parietal arteries.

(ii) Bilateral median anterior cerebral artery

The remaining four cases were all bilateral, therefore supplying both hemispheres. In Case 4 and 6 (Fig. 5.7), the same arteries arose bilaterally (the SIPA and paracentral lobule artery in Case 4, and the SIPA in Case 6) from the MedACA. The MedACA in Case 5 gave rise to two cortical branches on the left (SIPA and paracentral lobule artery) and three on the right (PLA and parietal arteries). In Case 7 the MedACA gave rise to the parietal arteries on the right, and the SIPA and paracentral lobule artery on the left.

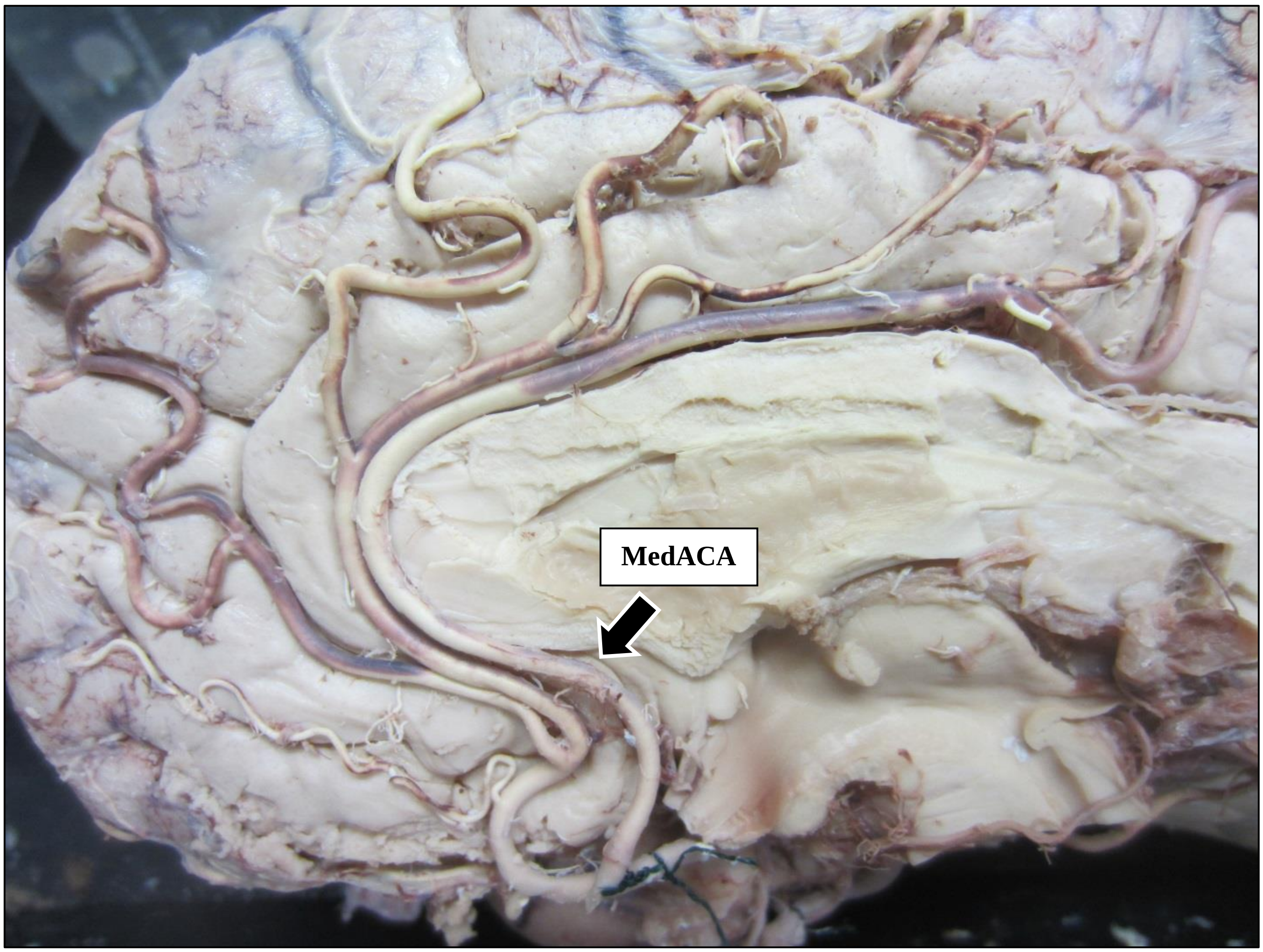

Figure 5.8: Median anterior cerebral artery.

5.4.3.2. Bihemispheric anterior cerebral artery

A bihemispheric ACA was observed in 19.8% in the present study and a line diagram of each case is given in Figure 5.9. The cortical branches arising from the bihemispheric branch is indicated in red. The bihemispheric branches originated between two paracentral lobule arteries in three cases, between the

PLA and the PIFA in three cases, and between the anterior and middle internal frontal arteries in three cases.

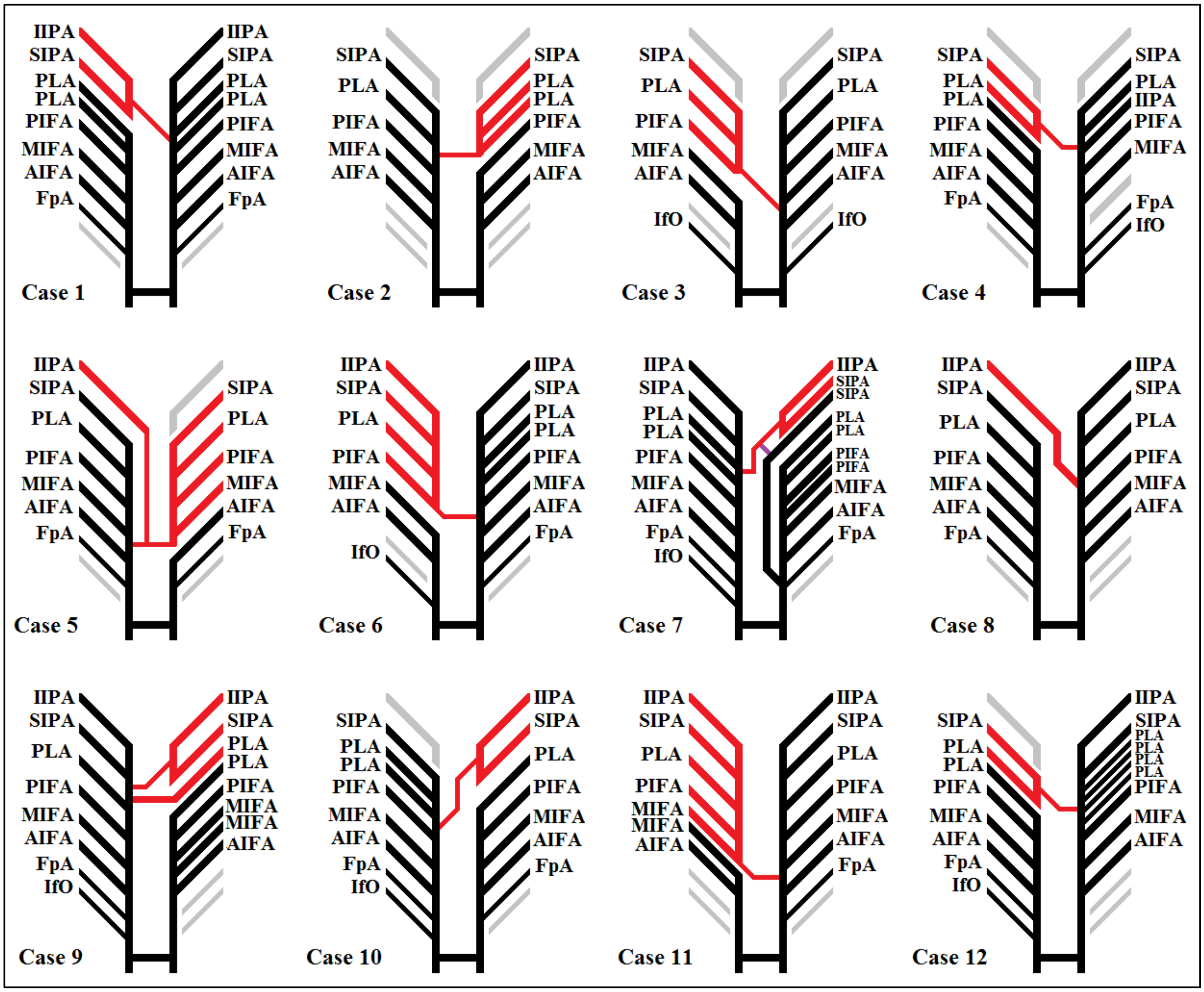

Figure 5.9: Bihemispheric anterior cerebral arteries observed in the present study.
(AIFA) Anterior internal frontal artery; (FpA) Frontopolar artery; (IfO) Infra-orbital artery; (IIPA) Inferior internal parietal artery; (MIFA) Middle internal frontal artery; (PLA) Paracentral lobule artery; (PIFA) Posterior internal frontal artery; and (SIPA) Superior internal parietal artery.

Excluding Case 5 and 9, the remaining 10 cases can be divided into two groups; one bihemispheric branch from the right to the left hemisphere (three cases), and one bihemispheric branch from the left to the right hemisphere (seven cases). When the bihemispheric branch gave rise to arteries from the left to the right hemisphere, one to five cortical branches originated from the bihemispheric branch. When the bihemispheric branch supplied arteries to the left side, two or three cortical branches originated from the bihemispheric branch.

In Case 5 the bihemispheric branch gave rise to a branch supplying the ipsilateral as well as the contralateral hemisphere. In Case 7 an anastomosis between the bihemispheric branch arising from the right ACA (giving origin to the left IIPA and SIPA) and the left superior internal parietal artery was observed. The diameter and length of this anastomosis was 0.9 mm and 2.0 mm, respectively. Case 8 was the only specimen where only one artery (IIPA) originated from the bihemispheric branch. This can also be viewed as an anomalous origin of the IIPA from the contralateral ACA and was also the only case where the SIPA did not originate from the bihemispheric branch. In Case 9 there were two bihemispheric branches observed in one specimen. The first branch gave rise to the PLA and the second branch to the parietal arteries. The most frequent cortical arteries arising from a bihemispheric branch were the SIPA in 11 out of 12 cases, and the IIPA and paracentral lobule artery in eight cases each.

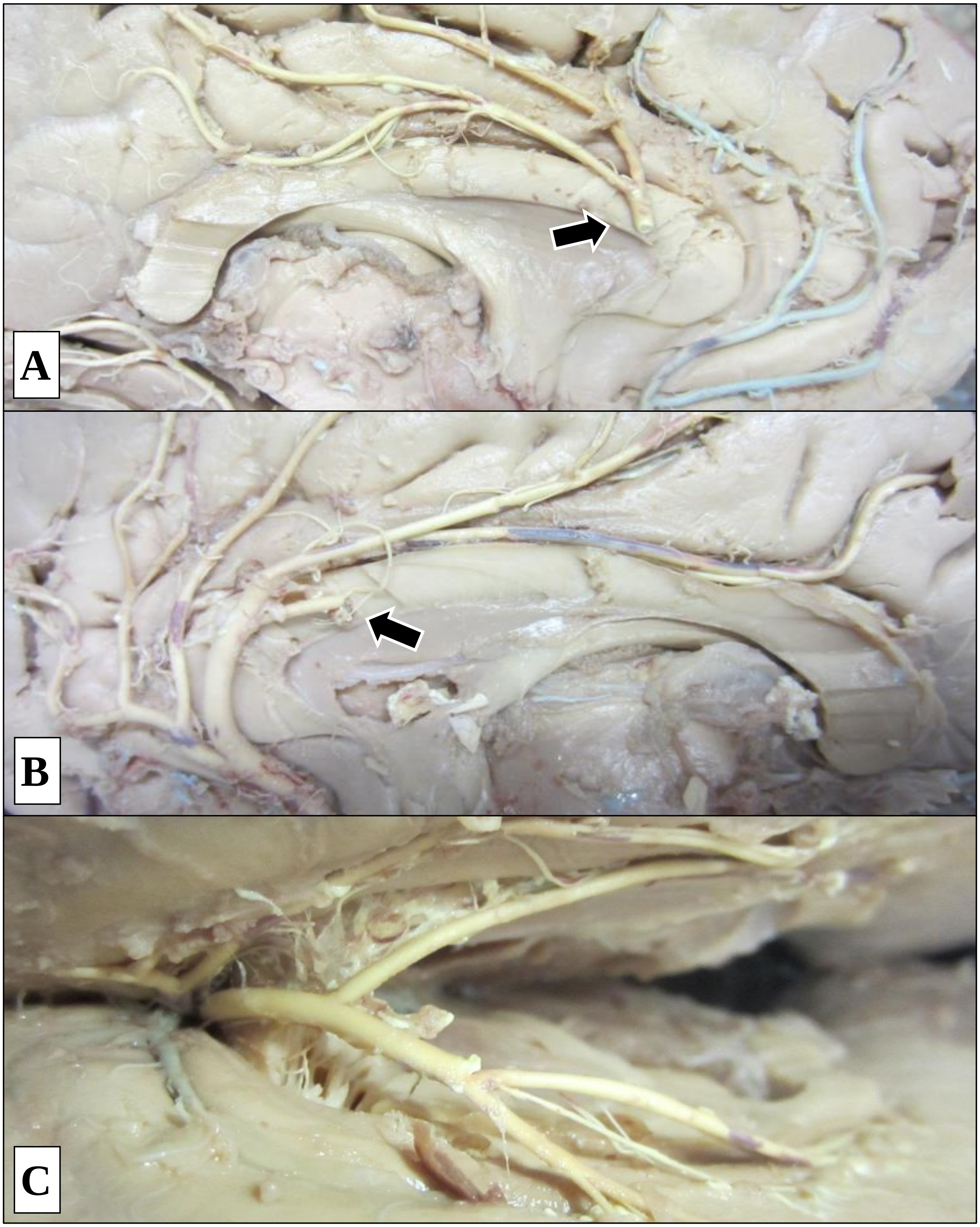

Figure 5.10: Bihemispheric anterior cerebral artery. A) Left hemisphere receiving branch from the right; B) Bihemispheric branch from the right to the left hemisphere; and C) Superior view.

The diameter and length of the bihemispheric and median anterior cerebral arteries were measured and the results are tabulated in Table 5.7. The diameters were measured at the origin of the BihemACA or MedACA. The cortical arteries that originated from the bihemispheric ACA and MedACA are also tabulated in Table 5.7. Length 1 refers to the distance of the origin of the artery (either BihemACA or MedACA) from the AcoA. The MedACA arose from the A2 segment in only one case (Case 1), therefore this was the only MedACA case with a measurement for Length 1. Length 2 refers to the length of the crossing branch, and the length of the MedACA before division into cortical branches. This is illustrated in Figure 5.11.

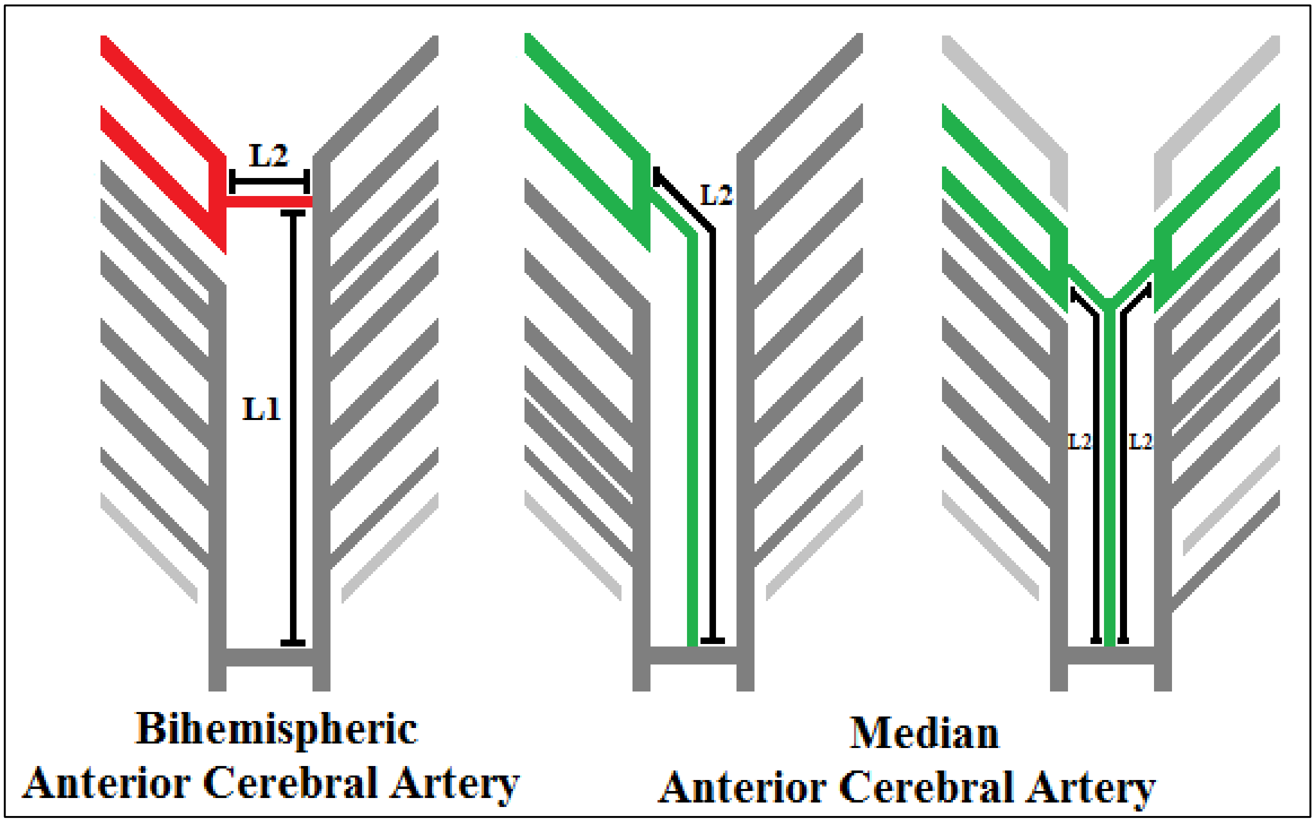

Figure 5.11: The measurements of the anomalies of the anterior cerebral artery.

Table 5.7: The diameter (mm), length (mm) and cortical arteries originating from the bihemispheric and median anterior cerebral artery.

Case	Variation	Diameter	Length 1	Length 2	Cortical Arteries	
					Right side	Left side
Case 1	BihemACA	1.8	57.0	41.5	SIPA, IIPA	-
Case 2	BihemACA	2.1	36.0	13.0	-	PLA, PLA, SIPA
Case 3	BihemACA	1.8	32.5	8.0	PIFA, PLA, SIPA	-
Case 4	BihemACA	1.8	42.7	25.0	PLA, SIPA	-
Case 5	BihemACA	2.4	36.7	5.7	IIPA	-
		-	36.7	18.7	-	MIFA, PIFA, PLA, SIPA
Case 6	BihemACA	2.2	40.0	33.0	PIFA, PLA, SIPA, IIPA	-
Case 7	BihemACA	1.9	64.7	19.0	-	SIPA, IIPA
Case 8	BihemACA	1.7	62.2	-	IIPA	-
Case 9	BihemACA					
	Branch 1:	1.1	63.0	-	-	PLA
	Branch 2:	1.4	69.0	13.0	-	SIPA, IIPA
Case 10	BihemACA	1.2	66.4	22.5	-	SIPA, IIPA
Case 11	BihemACA	2.0	26.0	17.5	MIFA, PIFA, PLA, SIPA, IIPA	-
Case 12	BihemACA	2.4	53.2	19.0	PLA, SIPA	-
Case 1	MedACA	2.0	7.5	60.0	PLA, SIPA	-
Case 2	MedACA	1.8	-	-	-	SIPA
Case 3	MedACA	1.7	-	95.0	SIPA, IIPA	-
Case 4	MedACA	1.7	-	Right: 100.7	PLA, PLA	-
				Left: 102.7	-	PLA, PLA
Case 5	MedACA	2.4	-	Right: 75.7	IIPA, PLA, SIPA	-
				Left: 71.5	-	PLA, SIPA
Case 6	MedACA	1.3	-	72.5	SIPA	SIPA
Case 7	MedACA	1.9	-	Right: 111.7	SIPA, IIPA	-
				Left: 105.9	-	PLA, SIPA

(BihemACA) Bihemispheric anterior cerebral artery; (IIPA) Inferior internal parietal artery; (MedACA) Median anterior cerebral artery; (MIFA) Middle internal frontal artery; (PIFA) Posterior internal frontal artery; (PLA) Paracentral lobule artery; and (SIPA) Superior internal parietal artery.

The average diameter of both the BihemACA and MedACA was 1.8 mm. Branches supplying the right side were larger, since the average diameter of bihemispheric branches on the right was 2.0 mm, and on the left 1.5 mm. Both the unilateral and the bilateral MedACA had an average diameter of 1.8 mm. The average distance of the origin of the BihemACA (Length 1) from the AcoA was 43.8 mm on the right, and 56.0 mm on the left.

The MedACA and the BihemACA can have very similar definitions. The definition for the BihemACA is the presence of a branch that supplies the contralateral hemisphere, where the ipsilateral ACA is hypoplastic or terminates early. The definition for the MedACA is the presence of an additional branch and the ACA or the A2 segments are still present and not hypoplastic. Additional classification is needed for these anomalies. Figure 5.12 illustrates the extended criteria of the median ACA, bihemispheric ACA and the unusual cortical artery.

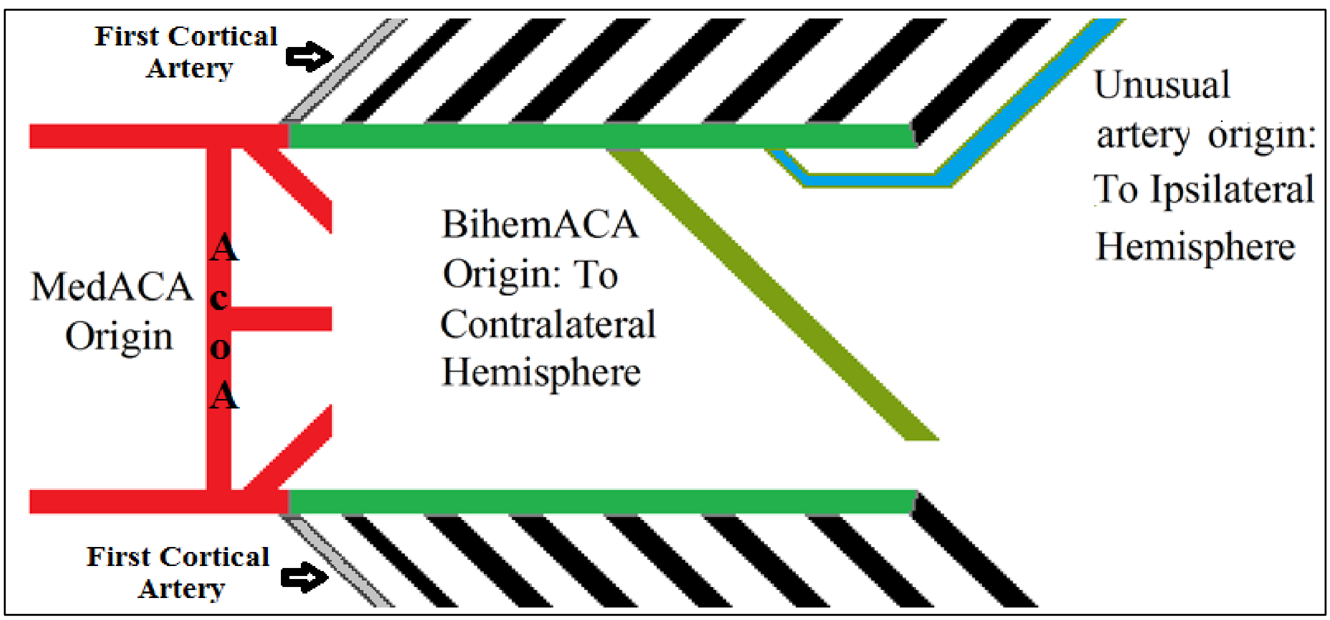

Figure 5.12: Clarification on the median anterior cerebral artery, the bihemispheric anterior cerebral artery, and unusual origin of a cortical artery.

If the abnormal artery originates proximal to the first cortical artery, it was considered a median ACA (artery can supply one or both hemispheres, or only one cortical artery). However, if the abnormal artery originates distal to the first cortical artery and supplies the contralateral hemisphere, it was considered a bihemispheric branch. Furthermore, if the unusual artery originates distal to the first cortical artery and supplies the ipsilateral hemisphere, it was considered a cortical artery with an abnormal origin.

5.5. PRESENT STUDY: MIDDLE CEREBRAL ARTERY

The present study consisted of 100 hemispheres to assess the anatomy of the MCA. This included 50 right, and 50 left hemispheres. The trunks, cortical branches, branching and anomalies of the MCA are described separately.

5.5.1. Trunks

The diameter of the M1 segment and trunks (superior, middle and inferior trunks) observed bilaterally, between males and females, the different population groups and in different age groups are given in Table 5.8. The diameter was measured at the origin. Few studies comment on these parameters.

The diameter of the M1 segment and the trunks (superior, middle and inferior trunks) had no statistically significant differences between the right and left sides, or between males and females. There was a statistically significant difference between the diameter of the M1 segment between the coloured and the white population group. The larger diameter was observed in the specimens from the white population group. There was also a statistically significant difference between the M1 segment diameter between the different age groups (Group 1 versus Group 2, and Group 1 versus Group 3). A statistically significant difference was found between the younger group and the older groups for the M1 diameter, although there were no statistically significant differences observed in the superior, middle or inferior trunks. The statistically significant differences are indicated in the table (Table 5.8).

The diameter and length of the M1 segment were measured by previous authors in similar studies[112, 113, 123, 124, 128, 231-233] and this is tabulated in Table 5.9. The predivision length was measured from the origin of the MCA to the main branching (end of main trunk).

Table 5.8: The average diameter (mm) of the M1 segment, superior, middle and inferior trunks observed bilaterally, between males and females, different population groups and different age groups.

Trunks		Average	Bilateral		Sex		Population Groups			Age Groups		
			Right	**Left**	**Male**	**Female**	**Group 1: Coloured**	**Group 2: Black**	**Group 3: White**	**Group 1: 22-34**	**Group 2: 35-48**	**Group 3: 49-75**
M1	**D**	2.9	2.9	2.9	2.9	2.8	2.8	2.9	**3.4**[B]	2.7	**2.9**[A]	**3.0**[B]
SUP	**D**	2.2	2.2	2.2	2.2	2.1	2.1	2.3	2.3	2.1	2.2	2.3
MID	**D**	2.0	1.9	2.0	2.0	1.7	1.9	1.8	2.3	2.0	1.7	2.0
INF	**D**	2.0	2.1	2.0	2.0	2.0	2.0	2.1	2.3	1.9	2.0	2.1

(D) Diameter; (INF) Inferior trunk; (MID) Middle trunk; and (SUP) Superior trunk.
([A]) Indicates a statistically significant difference ($p < 0.05$) between Group 1 and Group 2
([B]) Indicates a statistically significant difference ($p < 0.05$) between Group 1 and Group 3

Table 5.9: The diameter (mm) of the M1 segment and predivision length (mm)[112, 113, 123, 124, 128, 231-233].

<table>
<tr><th></th><th></th><th>Grellier et al. (1978)</th><th>van der Zwan et al. (1993)</th><th>Meneses et al. (1997)</th><th>Türe et al. (2000)</th><th>Idowu et al. (2002)</th><th>Tarasów et al. (2007)</th><th>Vuillier et al. (2008)</th><th>Zurada et al. (2011)</th><th>Sadatomo et al. (2013)</th><th>Present Study</th></tr>
<tr><td>R</td><td>Diameter</td><td rowspan="2">4.1</td><td>2.8</td><td rowspan="2">3.2</td><td rowspan="2">3.2</td><td rowspan="2">3.5</td><td>2.4</td><td rowspan="2">3.4</td><td>-</td><td>2.2</td><td>2.9</td></tr>
<tr><td>L</td><td>Diameter</td><td>2.7</td><td>2.5</td><td>-</td><td>2.2</td><td>2.9</td></tr>
<tr><td>R</td><td>Predivision length</td><td rowspan="2">16.6</td><td>-</td><td rowspan="2">18.5</td><td rowspan="2">23.4</td><td rowspan="2">15.4</td><td>14.5</td><td rowspan="2">13.0</td><td>15.5</td><td>-</td><td>19.7</td></tr>
<tr><td>L</td><td>Predivision length</td><td>-</td><td>13.8</td><td>15.7</td><td>-</td><td>20.9</td></tr>
</table>

(L) Left; (R) Right.

The predivision length observed in the present study was similar to the results of Meneses *et al.*[123] and Türe *et al*.[112]. The M1 segment diameter was similar to the results of van der Zwan *et al*.[231], Meneses *et al*.[123] and Türe *et al*.[112]. Not all authors give separate results for the right and left sides.

5.5.2. Cortical branches

There is still controversy on the most common course and origin of MCA branches[111]. The cortical branches of the MCA can arise as early branches, or from the superior, inferior or middle trunk. The size and the length of these cortical branches can vary, and very few studies comment on these aspects.

5.5.2.1. Diameter and length

The diameter and lengths of the MCA cortical branches are tabulated in Table 5.10. A comparison is made between the right and left, males and females, different population groups and different age groups. The arteries with the greatest diameter were the PPA and angular arteries. The smallest artery was the TpA (0.9 mm). The TpA was also the shortest (25.1 mm) and the angular artery the longest (93.7 mm). The angular artery can be seen as the terminal branch of the MCA.

Bilaterally there was a statistically significant difference in the diameter of the OfA and calcarine artery, and the length of the PPA. The length of the APA was the only statistically significant difference between males and females; males had a statistically significantly longer length. The diameter of the CTA was the only statistically significant difference between the population groups. Specimens from the white population group had a statistically significantly larger diameter compared to that of the coloured population group (1.6 mm and 1.3 mm, respectively). The diameter of the PPA was statistically significantly different between the different age groups (Group 1 versus Group 2, and Group 1 versus Group 3). The older groups (1.5 mm) had a statistically significantly larger diameter compared to the younger age group (1.3 mm). The length of the PfA, common temporal artery and the PTA was statistically significantly different between the younger and oldest age group (Group 1 versus Group 3). The length of the ToA was statistically significantly different between the younger (Group 1) and the older age group (Group 2). The statistically significant differences are indicated in the table (Table 5.10).

Table 5.10: The average diameter (mm) and length (mm) of the middle cerebral cortical branches observed bilaterally, between males and females, different population groups and different age groups.

Cortical Arteries		Average	Bilateral		Sex		Population Groups			Age Groups		
			Right	Left	Male	Female	Group 1: Coloured	Group 2: Black	Group 3: White	Group 1: 22-34	Group 2: 35-48	Group 3: 49-75
OfA	**D**	1.2	**1.16***	**1.24***	1.2	1.2	1.2	1.3	1.2	1.2	1.2	1.2
	L	37.8	40.3	35.2	37.0	39.3	37.0	37.3	48.2	35.7	36.2	40.7
PfA	**D**	1.3	1.3	1.3	1.3	1.2	1.2	1.3	1.4	1.2	1.3	1.3
	L	47.1	49.0	45.2	47.1	47.1	46.7	46.0	56.0	41.5	48.2	**51.9[B]**
PcA	**D**	1.3	1.3	1.3	1.3	1.4	1.3	1.3	1.3	1.2	1.3	1.3
	L	50.7	50.8	50.6	52.7	46.5	50.8	50.9	52.6	50.7	49.7	53.9
CA	**D**	1.3	**1.3***	**1.4***	1.3	1.3	1.3	1.4	1.3	1.2	1.4	1.4
	L	50.7	51.6	49.8	51.6	49.0	50.3	51.2	47.3	55.0	47.7	48.8
APA	**D**	1.3	1.3	1.4	1.3	1.4	1.3	1.3	1.4	1.3	1.3	1.3
	L	67.1	66.5	67.8	**70.1***	**60.3***	64.4	71.2	73.0	69.3	71.7	62.5
PPA	**D**	1.4	1.5	1.4	1.5	1.4	1.4	1.4	1.7	1.3	**1.5[A]**	**1.5[B]**
	L	80.7	**74.6***	**86.8***	80.4	81.6	83.2	76.5	85.9	80.9	73.4	83.4
AA	**D**	1.4	1.4	1.4	1.4	1.4	1.4	1.5	1.4	1.4	1.4	1.4
	L	93.9	89.9	98.0	91.8	97.6	95.9	93.9	79.8	93.3	102.2	84.5
ToA	**D**	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.5	1.2	1.3	1.4
	L	89.9	84.5	95.4	91.2	87.4	86.8	98.0	80.0	82.0	**108.3[A]**	81.5
CTA	**D**	1.3	1.3	1.4	1.3	1.4	1.3	1.4	**1.6[B]**	1.3	1.4	1.3
	L	25.4	25.7	25.1	27.7	21.1	25.5	25.1	26.5	19.8	24.9	**32.1[B]**
TpA	**D**	0.9	0.9	0.9	0.9	1.0	0.9	0.9	0.9	0.9	0.9	0.9
	L	25.1	25.6	24.6	24.3	26.8	27.2	23.8	20.6	25.5	26.2	25.3
ATA	**D**	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	L	39.2	39.8	38.6	39.6	38.4	38.4	41.1	40.8	37.2	41.2	40.6
MTA	**D**	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.2	1.0	1.0	1.0
	L	54.9	54.2	55.7	57.6	49.0	53.2	55.5	62.0	52.9	55.6	55.7
PTA	**D**	1.1	1.1	1.1	1.1	1.1	1.0	1.1	1.1	1.1	1.0	1.0
	L	79.1	74.5	83.7	78.4	81.1	84.7	68.3	85.2	73.2	69.8	**93.6[B]**

(AA) Angular artery; (APA) Anterior parietal artery; (ATA) Anterior temporal artery; (CA) Central artery; (CTA) Common temporal; (D) Diameter; (L) Length; (MTA) Middle temporal artery; (OfA) Orbitofrontal artery; (PcA) Precentral artery; (PfA) Prefrontal artery; (PPA) Posterior parietal artery; (PTA) Posterior temporal artery; (ToA) Temporooccipital artery; and (TpA) Temporopolar artery

(*) Indicates a statistically significant difference ($p < 0.05$)

([A]) Indicates a statistically significant difference ($p < 0.05$) between Group 1 and Group 2

([B]) Indicates a statistically significant difference ($p < 0.05$) between Group 1 and Group 3

5.5.2.2. Absence, duplication and triplication

The most consistent artery was the PfA, since it was always present and never duplicated or triplicated. The CTA was the most commonly absent artery in 51.0% of cases. The most duplicated arteries were the APA in 9.0% and the central artery in 8.0% of cases. The only triplicated arteries were the central and angular arteries in one case each.

5.5.2.3. Origins

For the description of the origins, the middle trunk was only described in the true trifurcation cases and not for proximal and lateral trifurcation. There were only six hemispheres that had a true trifurcation. In the other cases the cortical branches originated from either the superior trunk, inferior trunk, or as an early branch (Table 5.11). The MCA cortical branches can be described in three groups; the frontal branches, the parietal branches, and the temporal branches. The origins of the MCA cortical branches are tabulated in Table 5.11. The most common origins of the cortical branches are illustrated in Figure 5.13.

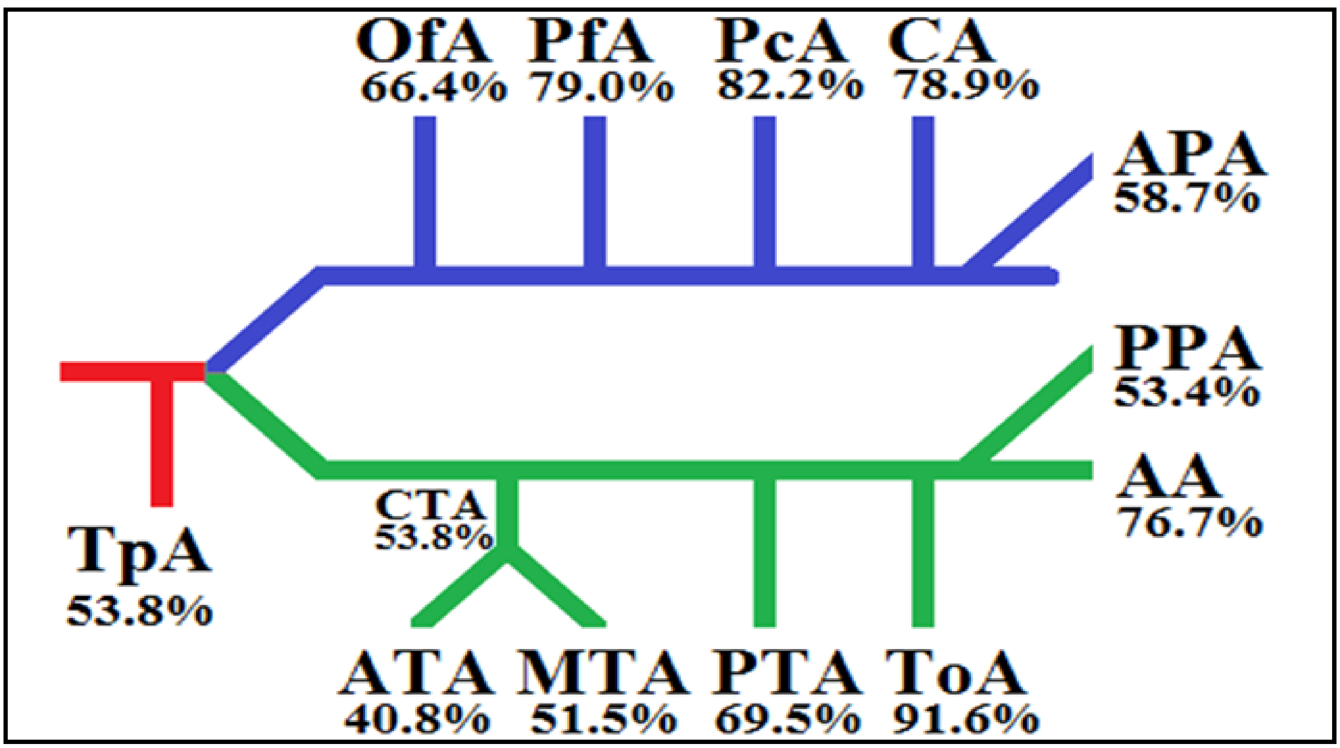

Figure 5.13: The most common origins of the middle cerebral cortical branches.
(AA) Angular artery; (APA) Anterior parietal artery; (ATA) Anterior temporal artery; (CA) Central artery; (CTA) Common temporal; (MTA) Middle temporal artery; (OfA) Orbitofrontal artery; (PcA) Precentral artery; (PfA) Prefrontal artery; (PPA) Posterior parietal artery; (PTA) Posterior temporal artery; (ToA) Temporooccipital artery; and (TpA) Temporopolar artery

Table 5.11: The presence, duplication, triplication and origin of the middle cerebral cortical branches observed in the present study.

	OfA	PfA	PcA	CA	APA	PPA	AA	CTA	TpA	ATA	MTA	PTA	ToA
Presence	99.0%	100%	99.0%	100%	100%	100%	97.0%	49.0%	90.0%	97.0%	94.0%	82.0%	95.0%
Duplicated	5.0%	-	2.0%	8.0%	9.0%	3.0%	5.0%	-	1.0%	1.0%	3.0%	-	-
Triplicated	-	-	-	1.0%	-	-	1.0%	-	-	-	-	-	-
EB	24.0%	21.0%	12.9%	3.7%	-	-	-	44.9%	53.8%	26.5%	4.1%	-	1.1%
INF	-	-	-	12.8%	34.9%	53.4%	76.7%	53.1%	20.9%	27.6%	36.1%	69.5%	91.6%
SUP	66.4%	79.0%	82.2%	78.9%	58.7%	42.7%	22.3%	-	-	-	-	-	5.3%
MID	-	-	1.0%	2.7%	5.5%	2.9%	1.0%	-	-	-	-	-	-
CTA	-	-	-	-	-	-	-	-	22.0%	40.8%	51.5%	19.5%	1.1%
PfA	9.6%	-	2.0%	-	-	-	-	-	-	-	-	-	-
CA	-	-	2.0%	-	0.9%	-	-	-	-	-	-	-	-
APA	-	-	-	2.7%	-	-	-	-	-	-	-	-	-
AA	-	-	-	-	-	1.0%	-	-	-	-	-	-	-
ATA	-	-	-	-	-	-	-	-	2.2%	-	-	-	-
MTA	-	-	-	-	-	-	-	-	1.1%	4.1%	-	1.2%	1.1%
PTA	-	-	-	-	-	-	-	-	-	1.0%	4.1%	-	-
ToA	-	-	-	-	-	-	-	2.0%	-	-	4.1%	9.8%	-

The diameter and length are given in millimetres (mm). (AA) Angular artery; (APA) Anterior parietal artery; (ATA) Anterior temporal artery; (CA) Central artery; (CTA) Common temporal; (EB) Early branch; (INF) Inferior trunk; (MID) Middle trunk; (MTA) Middle temporal artery; (OfA) Orbitofrontal artery; (PcA) Precentral artery; (PfA) Prefrontal artery; (PPA) Posterior parietal artery (PTA) Posterior temporal artery; (SUP) Superior trunk; (ToA) Temporooccipital artery; and (TpA) Temporopolar artery.

(i) The frontal branches

The OfA and prefrontal arteries frequently arose from the superior trunk in 66.4% and 79.0% of cases, respectively. The precentral and central arteries frequently arose from the superior trunk in 82.2% and 78.9%, respectively. Uncommon origins included the orbitofrontal artery arising from the PfA in 10 cases, and the central artery arising from the APA in three cases. The PcA originated from the prefrontal artery in two cases, and from the central artery in two cases.

(ii) The parietal branches

The APA most commonly originated from the superior trunk in 58.7% and origin from the inferior trunk was also frequent (34.9%). The posterior parietal artery and the angular artery usually branched from the inferior trunk in 53.4% and 76.7%, respectively, and from the superior trunk in 42.7% and 22.3%, respectively. Uncommon origins included the APA arising from the central artery in one case and the PPA arising from the angular artery in one case.

Common trunks were observed between the OfA and prefrontal artery in 19 cases and between the prefrontal artery and the PcA in 11 cases. The central and precentral artery had a common trunk in seven cases and the central artery and APA arose as a common trunk in two cases. In 76.9% the common trunks arose as an early frontal branch, and in 23.1% the trunks arose from the superior trunk.

(iii) The temporal and temporo-occipital branches

The temporal arteries usually originated either as early temporal branches, or from the inferior trunk. The anterior, middle and posterior temporal arteries could also originate from the common temporal artery. The temporopolar artery usually originated as an early temporal branch (53.8%). The anterior and middle temporal arteries usually originated from the common temporal artery in 40.8% and 51.5%, respectively. The ToA, PTA and common temporal artery frequently originated from the inferior trunk in 91.6%, 69.5% and 53.1% of cases, respectively. A common trunk between the temporopolar artery and ATA was observed in 25 cases, originating from either the inferior trunk (five cases) or as an early temporal branch (20 cases).

The common temporal artery was present in 49.0% of cases and there are three different configurations that can be observed. The CTA can give rise to the anterior and middle temporal arteries (67.3%), the middle and posterior temporal arteries (20.4%), or it can give rise to all three temporal arteries (12.2%).

The temporopolar artery can also originate from the CTA and this was observed in 20 cases. Table 5.12 and Figure 5.14 illustrate the 12 configurations of the temporal arteries. Cases with duplication or absence of the temporal arteries were excluded and only 33 cases remained.

Table 5.12: Configuration of the superior temporal arteries.

Type	CTA Origin	TpA Origin	ATA Origin	MTA Origin	PTA Origin	n=33	Cases
1	ETB	CTA	CTA	CTA	INF	27.3%	9
2	ETB	ETB	CTA	CTA	INF	9.1%	3
3	ETB	ETB	CTA	CTA	CTA	3.0%	1
4	ETB	ETB*	ETB*	CTA	CTA	3.0%	1
5	INF	CTA	CTA	CTA	CTA	9.1%	3
6	INF	INF	CTA	CTA	CTA	3.0%	1
7	INF	CTA	CTA	CTA	INF	12.1%	4
8	INF	ETB	CTA	CTA	INF	9.1%	3
9	INF	INF	CTA	CTA	INF	3.0%	1
10	INF	ATA	CTA	CTA	INF	3.0%	1
11	INF	ETB*	ETB*	CTA	CTA	12.1%	4
12	INF	INF*	INF*	CTA	CTA	6.1%	2

(ATA) Anterior temporal artery; (CTA) Common temporal; (ETB) Early temporal branch; (INF) Inferior trunk; (MTA) Middle temporal artery; (PTA) Posterior temporal artery; and (TpA) Temporopolar artery.
(*) Indicates a common trunk

The most common configuration was Type 1. In type 9, the common temporal artery originates as an early temporal branch, and gives rise to the ATA, MTA and temporopolar artery. The PTA originates from the inferior trunk and this was observed in nine cases.

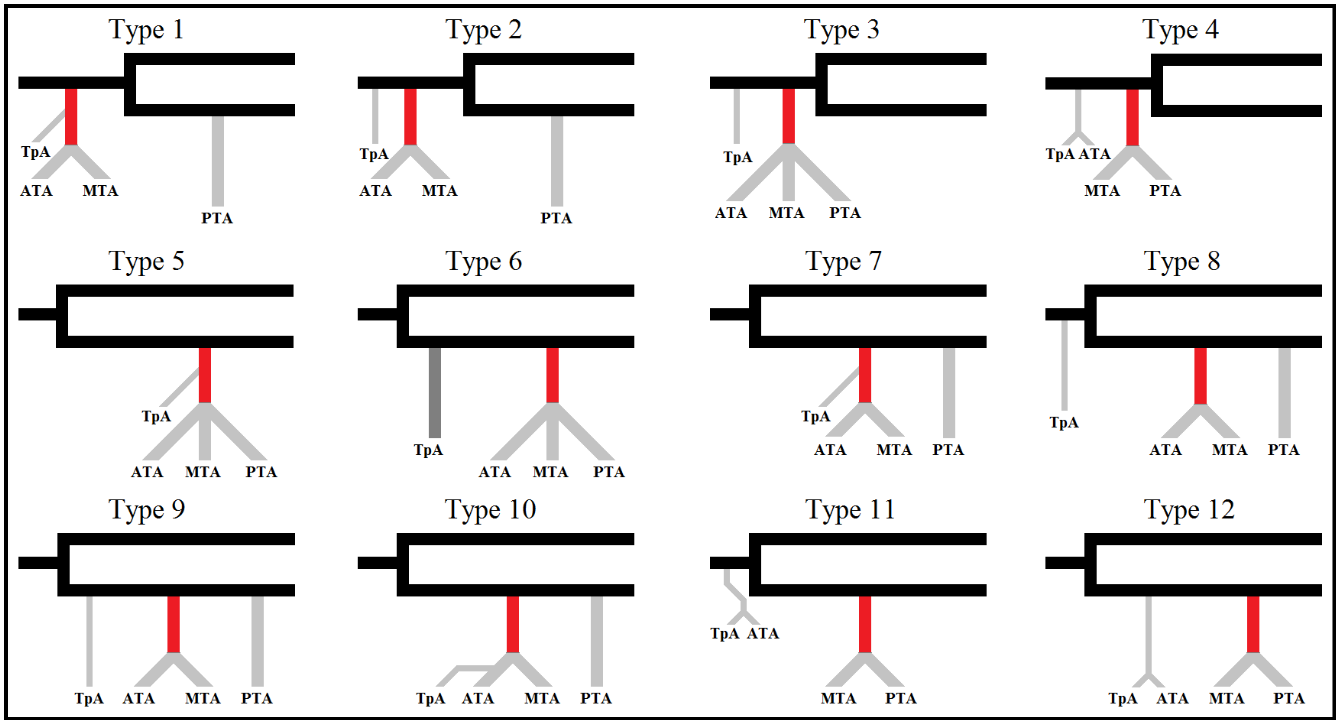

Figure 5.14: Configuration of the superior temporal arteries. (ATA) Anterior temporal artery; (MTA) Middle temporal artery; (PTA) Posterior temporal artery; and (TpA) Temporopolar artery.

5.5.2.4. Early branches

Early temporal branches were observed in 81.0%, and early frontal branches in 28.0% of cases. Both early temporal and early frontal branches were observed in 24.0% of cases. There were only 15 cases with no early branches in the present study.

5.5.3. Branching

In the case of bifurcation, the superior trunk usually gave origin to the OfA, PfA, precentral, and the central arteries. The parietal and angular arteries originated from either the superior or the inferior trunks. The inferior trunk gave origin to the temporal and temporo-occipital arteries.

True trifurcation was only observed in six cases and line diagrams of these cases are demonstrated in Figure 5.15. When trifurcation was observed, the superior trunk usually gave origin to the OfA, PfA and precentral arteries. The middle branch gave origin to the central artery (three cases), APA (five cases) and PPA (three cases). The PcA and angular arteries originated from the middle trunk in one case each. The inferior trunk usually gave origin to the temporal and temporo-occipital arteries. This is in accordance with what is described in the literature.

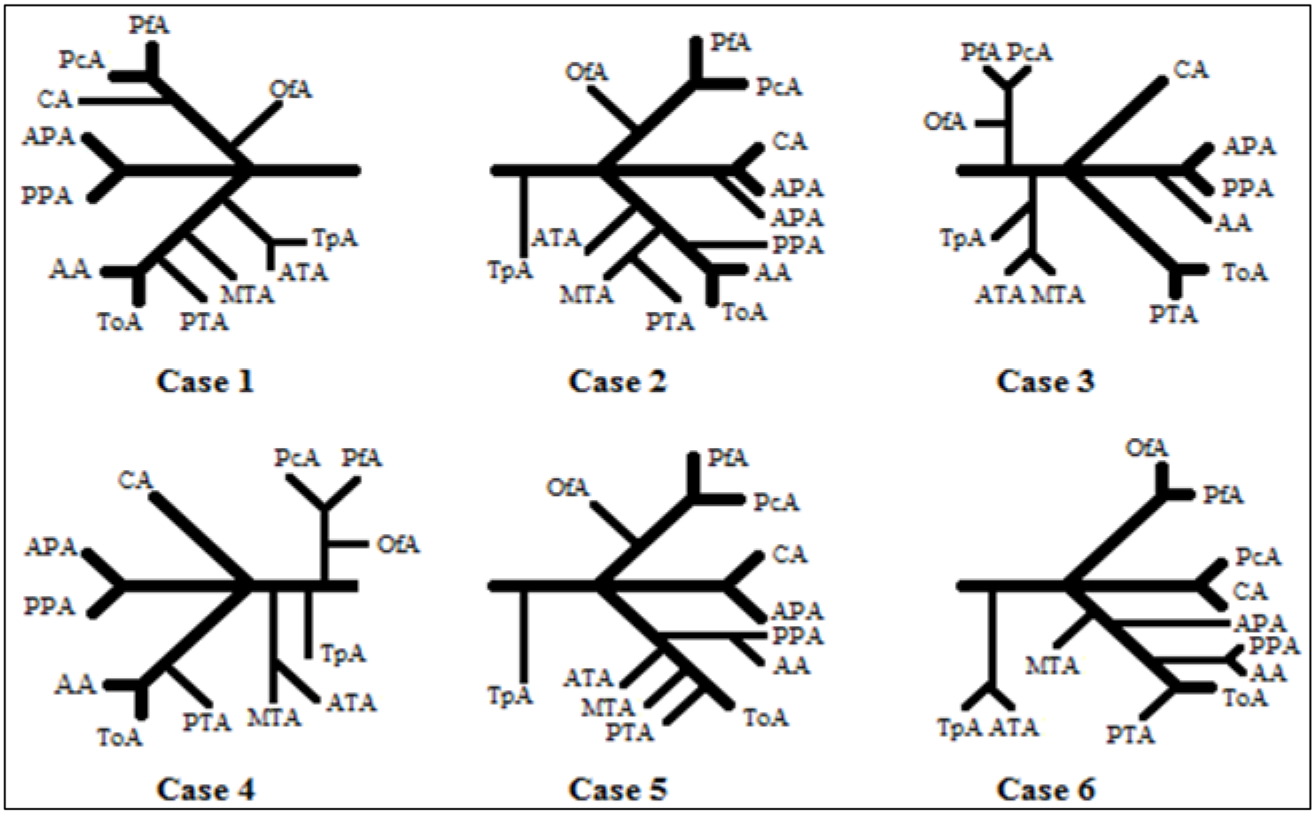

Figure 5.15: The six cases of true trifurcation of the middle cerebral artery.
(AA) Angular artery; (APA) Anterior parietal artery; (ATA) Anterior temporal artery; (CA) Central artery; (CTA) Common temporal artery; (MTA) Middle temporal artery; (OfA) Orbitofrontal artery; (PcA) Precentral artery; (PfA) Prefontal artery; (PPA) Posterior parietal artery; (PTA) Posterior temporal artery; (ToA) Temporooccipital artery; and (TpA) Temporopolar artery.

The different branching patterns were grouped into 11 different types (Fig. 2.6) and the results are tabulated in Table 5.13. The branching subtypes were compared bilaterally, between males and females, different population groups and different age groups. There were no cases of monofurcation, pseudotrifurcation, tetrafurcation or pseudotetrafurcation observed in the present study. The most common branching pattern was medial bifurcation in 34.0% of cases. Most authors only mention bifurcation and trifurcation and do not elaborate on the different subtypes.

Table 5.13: The prevalence of the MCA branching observed bilaterally, between males and females, different population groups and in different age groups.

	Total	Bilateral		Sex		Population group				Age			
		Right	Left	Male	Female	Group 1: Coloured	Group 2: Black	Group 3: White	Unknown	Group 1: 22-34	Group 2: 35-48	Group 3: 49-75	Unknown
True Trif.	6.0%	2.0%	4.0%	5.0%	1.0%	3.0%	1.0%	2.0%	-	-	1.0%	4.0%	1.0%
Proximal Trif.	9.0%	4.0%	5.0%	5.0%	4.0%	6.0%	1.0%	-	2.0%	3.0%	1.0%	3.0%	2.0%
Distal Trif.	9.0%	4.0%	5.0%	8.0%	1.0%	5.0%	3.0%	1.0%	-	4.0%	1.0%	4.0%	-
Medial Bif.	34.0%	21.0%	13.0%	18.0%	16.0%	21.0%	8.0%	5.0%	-	10.0%	9.0%	11.0%	4.0%
Lateral Bif.	22.0%	12.0%	10.0%	17.0%	5.0%	11.0%	11.0%	-	-	8.0%	9.0%	4.0%	1.0%
Medial pseudobif.	10.0%	4.0%	6.0%	10.0%	-	3.0%	7.0%	-	-	1.0%	5.0%	3.0%	1.0%
Lateral pseudobif.	9.0%	2.0%	7.0%	5.0%	4.0%	6.0%	3.0%	-	-	2.0%	3.0%	3.0%	1.0%
Early Bif.	1.0%	1.0%	-	-	1.0%	1.0%	-	-	-	-	-	1.0%	-

(Bif) Bifurcation; (Trif) Trifurcation.

Bifurcation was observed in 75 cases, and these cases were further divided into medial bifurcation (34.0%), lateral bifurcation (22.0%), medial pseudobifurcation (10.0%) and lateral pseudobifurcation (9.0%). True trifurcation was observed in six cases only, proximal trifurcation in nine cases and distal trifurcation in nine cases. A digital image of each of these branching types is given in Figure 5.16. There was a statistically significant difference ($p < 0.05$) between the branching subtypes between males (n=68) and females (n=32). Males had more distal trifurcation, lateral bifurcations and medial pseudobifurcation.

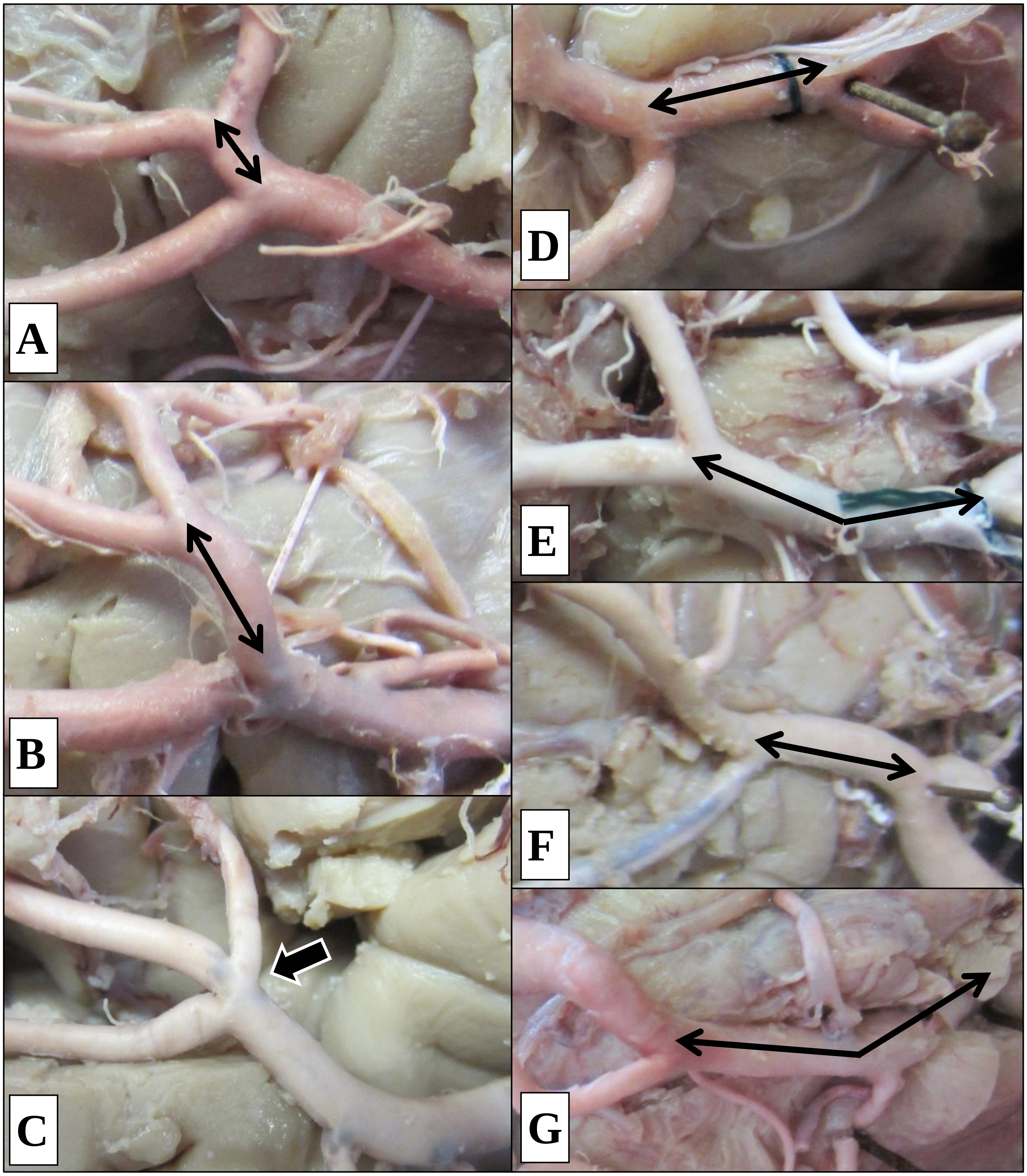

Figure 5.16: The middle cerebral artery branching subtypes. A) Proximal trifurcation; B) Distal trifurcation; C) True trifurcation; D) Medial bifurcation; E) Lateral bifurcation; F) Medial pseudobifurcation; and G) Lateral pseudobifurcation.

5.5.4. Anomalies

No cases of a duplicated MCA, accessory MCA or fenestration of the middle cerebral artery were observed in the present study. True anomalies of the middle cerebral artery are very rare, especially in comparison to anomalies in the anterior and posterior cerebral arteries.

5.2. PRESENT STUDY: POSTERIOR CEREBRAL ARTERY

The present study consisted of 124 hemispheres to assess the anatomy of the PCA. This included 62 right and 62 left hemispheres. The segments, cortical branches, branching and anomalies of the PCA are described separately.

5.2.1. Segments

The diameter and lengths of the PCA segments were measured and are tabulated in Table 5.14. A comparison is made between the right and left sides, males and females, different population groups and different age groups. Very few studies have measured the diameter and lengths of the PCA segments[9, 200].

The only bilateral statistically significant difference was the diameter of the P2P segment (larger on the left). The only statistically significant difference between males and females was the length of the P3 segment (longer in males). The diameter of the PCA segments and the length of the P3 segment, were statistically significantly different in the different population groups (Group 1 versus Group 3). The P3 segment in specimens from the white population group (Group 3) had larger diameters, and a longer length. There was a statistically significant difference between the different age groups in the diameter of all three segments, and between the lengths of the P2A and P2P segments. The older groups had a larger diameter and a longer length compared to the younger age group. There were no statistically significant differences between Group 2 and Group 3 in either the population groups or between the age groups. The statistically significant differences are indicated in the Table (Table 5.14).

Table 5.14: The average diameter (mm) and length (mm) of the P2A, P2P and P3 segments observed bilaterally, between males and females, different population groups and different age groups.

Segments		Average	Bilateral		Sex		Population Groups			Age Groups		
			Right	Left	Male	Female	Group 1: Coloured	Group 2: Black	Group 3: White	Group 1: 22-34	Group 2: 35-48	Group 3: 49-84
P2A	**D**	2.2	2.3	2.2	2.3	2.2	2.2	2.3	**2.6[B]**	2.0	**2.2[A]**	**2.3[B]**
	L	39.0	39.7	38.3	39.8	37.2	38.4	39.5	39.8	36.3	39.7	**40.7[B]**
P2P	**D**	1.5	**1.5***	**1.6***	1.5	1.5	1.5	1.6	**1.8[B]**	1.4	1.5	**1.6[B]**
	L	13.4	13.9	13.0	13.6	13.1	13.4	13.8	13.2	12.2	13.4	**14.7[B]**
P3	**D**	1.3	1.3	1.4	1.4	1.3	1.3	1.4	**1.6[B]**	1.2	**1.4[A]**	**1.4[B]**
	L	23.1	22.7	23.6	**23.9***	**21.4***	22.0	23.8	**29.0[B]**	22.7	23.8	22.3

(D) Diameter; (L) Length.
(*) Indicates a statistically significant difference ($p < 0.05$)
([A]) Indicates a statistically significant difference ($p < 0.05$) between Group 1 and Group 2
([B]) Indicates a statistically significant difference ($p < 0.05$) between Group 1 and Group 3

5.2.2. Cortical branches

The diameter and length of the PCA cortical branches were measured. Any absence, duplication or triplications were reported and the origins of the branches were noted. Few studies have noted these aspects.

5.2.2.1. Diameter and Length

The diameter and lengths of the PCA cortical branches were measured and are tabulated in Table 5.15. A comparison is made between the right and left, males and females, different population groups and different age groups. Very few studies have measured the diameter and lengths of the PCA cortical branches[88]. The arteries with the greatest diameter were the CTA (1.5 mm) and PoA (1.3 mm). The smallest artery was the SA (0.8 mm), and the calcarine artery and PoA were the longest (93.7 mm).

The length of the AITA and the diameter of the PoA were bilaterally statistically significantly different. The diameter of the CTA was statistically significantly larger in males, and the length of the CA and PoA was statistically significantly longer in males. The diameter of the CTA was statistically significantly larger in Group 2 (specimens from the black population group) and Group 3 (specimens from the white population group) compared to the coloured population group (Group 1). The diameter of the SA was statistically significantly larger in the white population group (Group 3) compared to the other population groups. The lengths of the CA and PoA were statistically significantly longer in the white population group compared to the other population groups. There was a statistically significant difference between the diameters of the CTA and PoA in comparison between the older age groups (Group 2 and Group 3) and the youngest age group (Group 1). The length of the CTA was statistically significantly longer in Group 2, compared to the youngest age group. There were no statistically significant differences between Group 2 and Group 3 in either the population groups or between the age groups. The statistically significant differences are indicated in the table (Table 5.15).

Table 5.15: The average diameter (mm) and length (mm) of the posterior cerebral cortical branches observed bilaterally, between males and females, different population groups and different age groups.

Cortical Arteries		Average	Bilateral		Sex		Population Groups			Age Groups		
			Right	Left	Male	Female	Group 1: Coloured	Group 2: Black	Group 3: White	Group 1: 22-34	Group 2: 35-48	Group 3: 49-84
CTA	**D**	1.5	1.5	1.5	**1.6***	**1.3***	1.3	**1.7[A]**	**1.9[B]**	1.2	**1.7[A]**	**1.6[B]**
	L	26.2	27.0	25.4	27.7	22.7	25.2	26.3	30.3	21.6	**28.5[A]**	27.3
AITA	**D**	0.9	0.9	0.9	0.9	0.8	0.9	0.9	0.9	0.8	0.9	0.9
	L	24.8	**27.0***	**22.4***	25.0	24.0	23.9	26.3	24.4	25.7	24.1	24.4
MITA	**D**	1.1	1.0	1.1	1.1	1.0	1.0	1.1	1.0	1.0	1.1	1.0
	L	34.1	36.1	32.1	34.6	32.6	32.9	35.7	35.6	31.7	34.2	34.3
PITA	**D**	1.2	1.3	1.2	1.3	1.2	1.2	1.3	1.3	1.2	1.3	1.2
	L	36.6	37.5	35.4	37.4	34.3	34.8	37.9	40.9	34.4	35.8	36.8
CA	**D**	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.2	1.1	1.1	1.1
	L	54.0	53.2	54.8	**57.0***	**47.0***	51.9	54.7	**64.9[B]**	52.3	52.1	56.8
PoA	**D**	1.3	**1.26***	**1.34***	1.3	1.3	1.3	1.3	1.5	1.2	**1.3[A]**	**1.3[B]**
	L	53.8	52.9	54.7	**57.1***	**46.3***	51.9	54.3	**64.9[B]**	51.4	52.9	56.5
SA	**D**	0.8	0.8	0.8	0.8	0.8	0.8	0.8	**1.1[B]**	0.8	0.8	0.9
	L	51.6	52.1	51.1	50.8	53.5	51.4	52.8	53.2	47.4	59.2	50.4

(AITA) Anterior inferior temporal artery; (CA) Calcarine artery; (CTA) Common temporal artery; (D) Diameter; (L) Length; (MITA) Middle inferior temporal artery; (PITA) Posterior inferior temporal artery; (PoA) Parieto-occipital artery; and (SA) Splenial artery.
(*) Indicates a statistically significant difference ($p < 0.05$)
([A]) Indicates a statistically significant difference ($p < 0.05$) between Group 1 and Group 2
([B]) Indicates a statistically significant difference ($p < 0.05$) between Group 1 and Group 3

5.2.2.2. Absence, duplication and triplication

The calcarine and parieto-occipital arteries were the most consistent, since these cortical branches were observed in all hemispheres and were each only duplicated once. Most commonly absent was the common temporal artery in 72.6%, and the splenial artery in 63.7% of cases. The anterior and posterior inferior temporal arteries were typically duplicated, both in 10.5% of specimens. The AITA and PITA was also the only arteries to be triplicated (Fig. 5.17). This was observed in three cases (2.4%) and one case (0.8%), respectively.

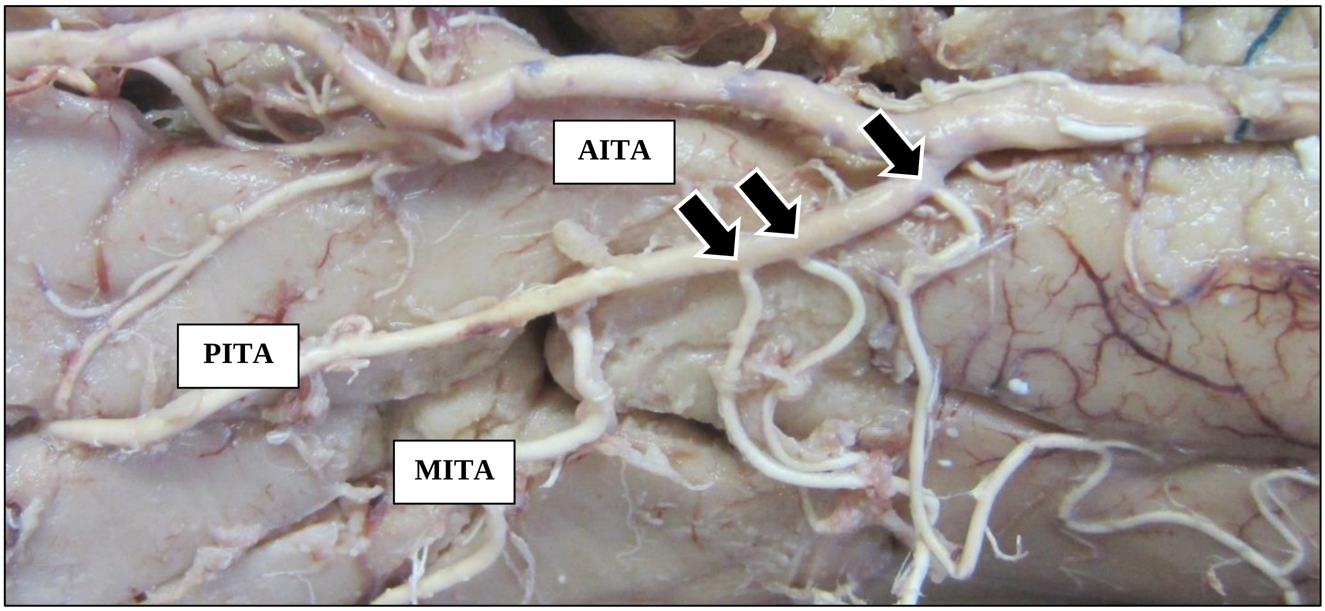

Figure 5.17: Triplicated anterior inferior temporal artery (arrows indicate the three arteries). (AITA) Anterior inferior temporal artery; (MITA) Middle inferior temporal artery; and (PITA) Posterior inferior temporal artery.

5.2.2.3. Origins

The origins of the PCA cortical branches are tabulated in Table 5.16. The common temporal artery originated from the P2A segment in all 34 cases (100%) and the temporal arteries most commonly originated from the P2A segment. The PoA and the calcarine artery typically originated from the P3 segment, whereas the splenial artery usually originated from the PoA (20 cases).

Table 5.16: The presence, duplication, triplication and origin of the posterior cerebral cortical branches observed in the present study.

	CTA	AITA	MITA	PITA	CA	PoA	SA
Presence	27.4%	96.0%	91.9%	99.2%	100%	100%	36.3%
Duplicated	-	10.5%	3.2%	10.5%	0.8%	0.8%	-
Triplicated	-	2.4%	-	0.8%	-	-	-
P2A Segment	100%	63.2%	50.0%	62.0%	12.0%	13.6%	17.8%
P2P Segment	-	-	0.8%	10.2%	20.0%	20.0%	8.9%
P3 Segment	-	-	-	2.2%	65.6%	64.8%	15.6%
P4 Segment	-	-	-	-	0.8%	0.8%	-
CTA	-	21.3%	29.7%	19.0%	-	-	-
AITA	-	-	1.7%	-	-	-	-
MITA	-	6.6%	-	0.7%	-	-	-
PITA	-	8.1%	16.1%	-	1.6%	-	4.4%
PoA	-	-	-	1.5%	-	-	44.4%
CA	-	0.7%	1.7%	4.4%	-	0.8%	8.9%

(AITA) Anterior inferior temporal artery; (CA) Calcarine artery; (CTA) Common temporal artery; (MITA) Middle inferior temporal artery; (PITA) Posterior inferior temporal artery; (PoA) Parieto-occipital artery; and (SA) Splenial artery.

Unusual origins included the anterior inferior temporal artery arising from the PITA in 11 cases (8.1%), and from the MITA in nine cases (6.6%). The middle inferior temporal artery arose from the PITA in 19 cases (16.1%), and the PITA arose from the calcarine artery in six cases (4.4%). Unusual origins of the PoA included an origin from the calcarine artery in one case (0.8%) and the calcarine artery arising from the PITA in two cases (1.6%).

A common temporal artery was present in 34 cases. A common trunk typically bifurcates at almost a 90 degree angle and the cortical branches have similar diameters. The CTA can be absent, supply all three temporal arteries, or only supply two temporal arteries. The common temporal artery gave origin to all three inferior temporal arteries in 44.1%, to the anterior and middle inferior temporal arteries in 14.7%, and to the middle and posterior inferior temporal arteries in 41.2%.

This study proposes a revised classification of the inferior temporal arteries, which excludes the hippocampal arteries, and takes into account the origins of the inferior temporal cortical branches of the PCA. The configuration of the temporal arteries was divided into 16 types according to the different origins (illustrated in Figure 5.18). Cases with duplication, triplication or absent temporal arteries were excluded and 84 cases remained. The configuration of the temporal arteries, with and without the CTA is tabulated in Table 5.17 and illustrations are given (Fig. 5.18).

Table 5.17: Configuration of the inferior temporal arteries.

Type	CTA	AITA Origin	MITA Origin	PITA Origin	n=84	Cases
1	Yes	CTA	CTA	CTA	7.1%	6
2	Yes	CTA	CTA	P2A Segment	7.1%	6
3	Yes	P2A Segment	CTA	CTA	14.3%	12
4	Yes	MITA	CTA	CTA	1.2%	1
5	No	P2A Segment	P2A Segment	P2A Segment	32.1%	27
6	No	P2A Segment	PITA	P2A Segment	9.5%	8
7	No	MITA	P2A Segment	P2A Segment	6.0%	5
8	No	P2A Segment	P2A Segment	P2P Segment	4.8%	4
9	No	PITA	PITA	P2A Segment	4.8%	4
10	No	P2A Segment	P2A Segment	Calcarine artery	3.6%	3
11	No	MITA	P2A Segment	P2P Segment	2.4%	2
12	No	P2A Segment	AITA	P2A Segment	2.4%	2
13	No	P2A Segment	P2P Segment	P2P Segment	1.2%	1
14	No	P2A Segment	P2A Segment	MITA	1.2%	1
15	No	P2A Segment	Calcarine artery	Calcarine artery	1.2%	1
16	No	Calcarine artery	Calcarine artery	Calcarine artery	1.2%	1

(AITA) Anterior inferior temporal artery; (CTA) Common temporal artery; (MITA) Middle inferior temporal artery; and (PITA) Posterior inferior temporal artery.

When the CTA was present, the most common configuration was Type 3 (MITA and PITA arise from common temporal artery, anterior inferior temporal artery from the P2A segment) in 12 cases (14.3%). Type 5 (all three inferior temporal branches arise from P2A segment) was the most common configuration in 27 of 84 cases (32.1%). These 16 types do not describe all possible configurations, only the configurations observed in the present study.

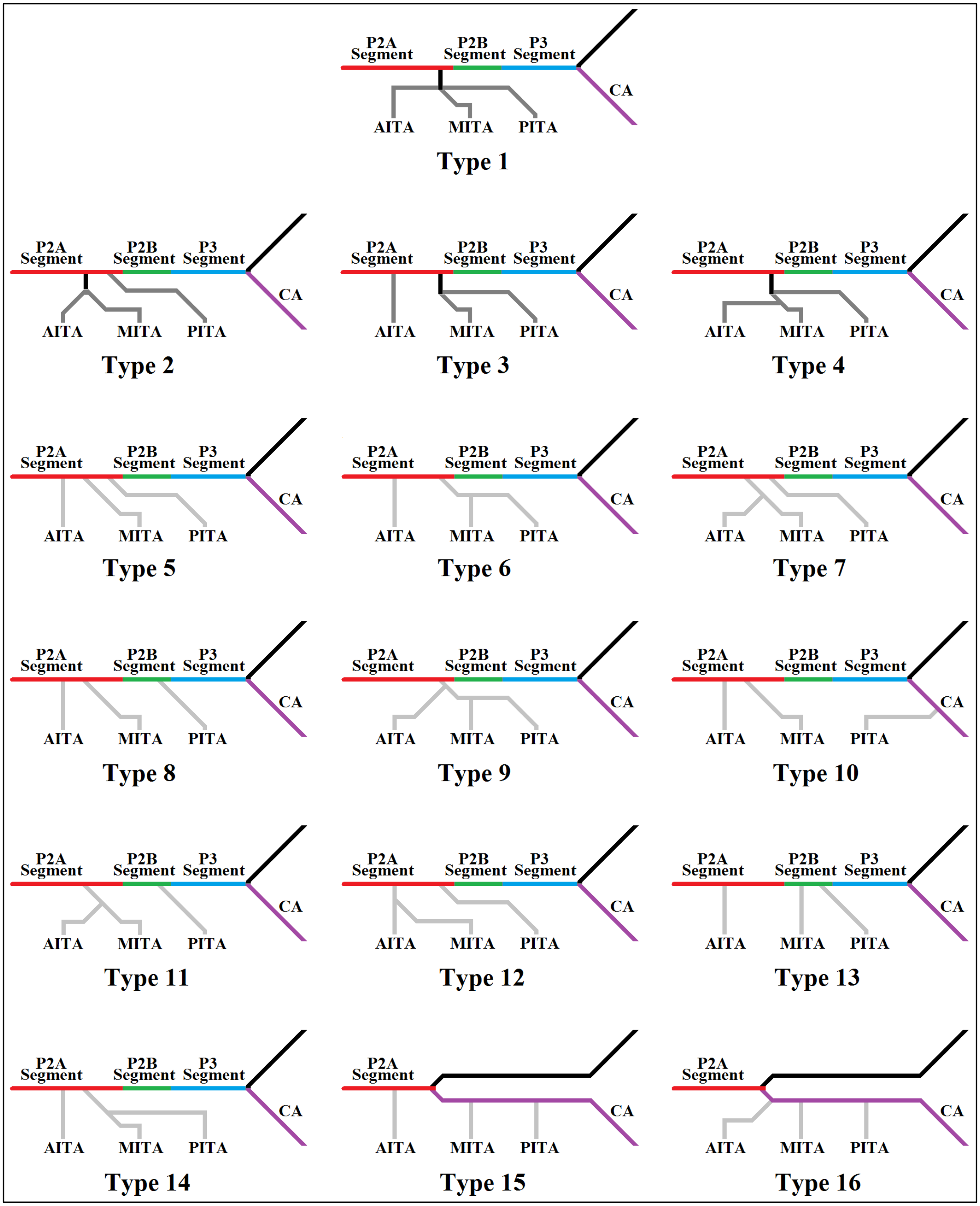

Figure 5.18: Configuration of the inferior temporal arteries.
(AITA) Anterior inferior temporal artery; (CA) Calcarine artery; (MITA) Middle inferior temporal artery; and (PITA) Posterior inferior temporal artery.

5.2.3. Branching

Three branching patterns of the distal PCA have previously been described by Milisavljević *et al*.[197]. In Type 1 the terminal division is at the P3 or P4 segment. In Type 2 the terminal division is at the P3 or P4 segment with the common temporal artery present. In Type 3 the terminal division is at the P2 segment. In the present study, Type 1, Type 2 and Type 3 were observed in 61 cases (50.0%), 21 cases (17.2%), and 40 cases (32.8%), respectively. Two hemispheres were excluded where a terminal division was not observed. In both cases the calcarine artery originated from the PITA. Therefore only 122 hemispheres were used for this analysis. These three branching types were further classified into seven subtypes (Table 5.18).

Table 5.18: The branching subtypes of the posterior cerebral artery.

Type	Terminal division point	CTA Present	Cases	Total (n=122)	Percentage
Type 1	P3 Segment	No	61	61 Cases	50.0%
Type 2	P3 Segment	Yes	20	21 Cases	17.2%
	P4 Segment	Yes	1		
Type 3	P2A Segment	No	12	40 Cases	32.8%
	P2A Segment	Yes	3		
	P2P Segment	No	16		
	P2P Segment	Yes	9		

Type 2, as described by Milisavljević *et al*.[197], was classified into two subtypes, terminal division at the P3 segment, and terminal division at the P4 segment. Type 3 was classified into four subtypes, depending on the origin (P2A or P2P segment) of the terminal division and the presence of the CTA. The prevalence of these subtypes is tabulated in Table 5.18. Type 3 can be viewed as early branching, and this is illustrated in Figure 5.19.

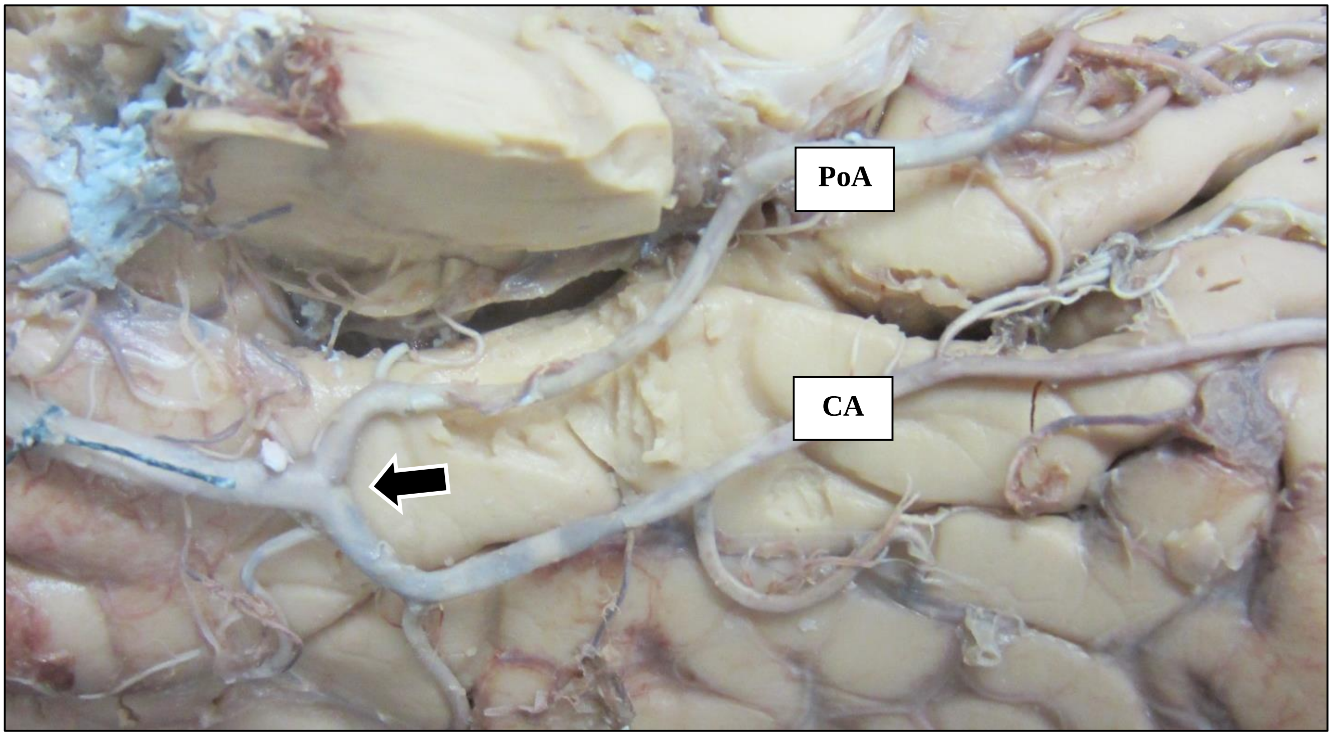

Figure 5.19: Early branching of the posterior cerebral artery (arrow indicates branching point). (CA) Calcarine artery; and (PoA) Parieto-occipital artery.

As described in the pilot study (section 5.3 pp. 57, 58), the PCA branching can be classified into monofurcation, bifurcation and trifurcation. This should not be confused with duplication or triplication of the PCA. When monofurcation is present there is no branching before the origin of the PoA and calcarine artery. This is the typical configuration described in the literature (the normal branching pattern). This was observed in only 34 cases (27.4%) in the present study.

In bifurcation there is an additional branching before the origin of the calcarine artery and PoA. The bifurcation branching type was observed in 84 cases (67.7%) in the present study. The bifurcation was due to the origin of the PITA in 52 cases, the origin of the common temporal artery in 25 cases, and the origin of the MITA in seven cases. In trifurcation there is also additional branching (three trunks) before the origin of the calcarine artery and PoA. The trifurcation branching type was observed in six cases (4.8%) in the present study. This was due to origin of the PITA and MITA (three cases) at the same place, or origin of the PITA and calcarine artery (three cases). An example of monofurcation, bifurcation and trifurcation type is given in Figure 5.20.

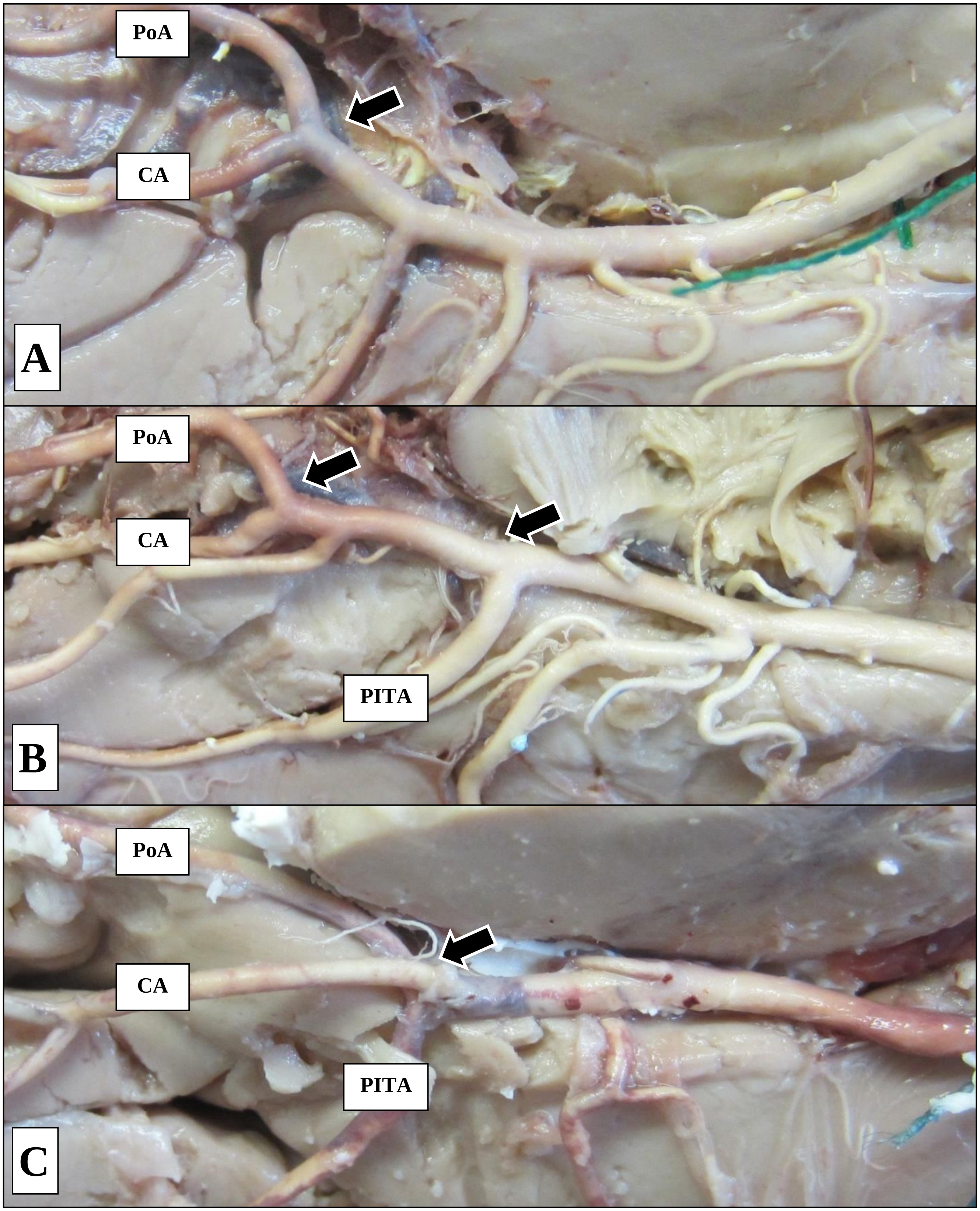

Figure 5.20: The branching patterns of the posterior cerebral artery. A) Monofurcation; B) Bifurcation; and C) Trifurcation (arrows indicate branching points).
(CA) Calcarine artery; (PITA) Posterior inferior temporal artery; and (PoA) Parieto-occipital artery.

5.2.4. Anomalies

Duplication or triplication of the PCA was not observed in the present study; however, there were two cases (1.6%) of fenestration of the P2A segment. These two cases are illustrated in Figure 5.21.

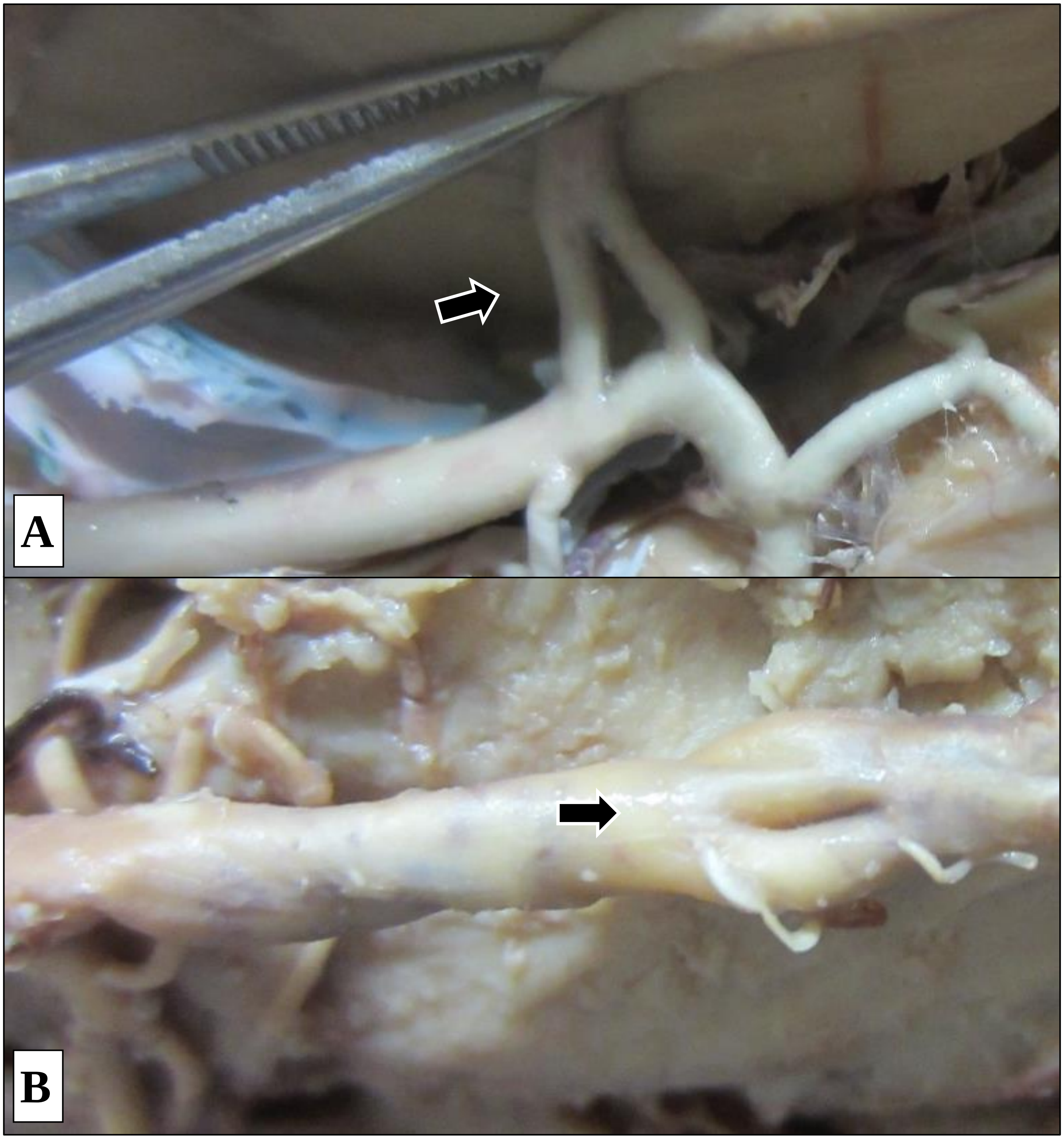

Figure 5.21: Fenestration of the right (A) and left (B) posterior cerebral artery (arrow indicates fenestration).

This first fenestration case (Fig. 5.21A) was similar to the case observed in the pilot study (Fig 5.2). It was located on the right P2A segment near the origin of the middle inferior temporal artery, and the opening was long and convex-like. The second fenestration (Fig. 5.21B) had a very small slit-like opening and was located on the left P2A segment.

CHAPTER SIX

DISCUSSION

6.1. ANTERIOR CEREBRAL ARTERY

6.1.1. Diameter and length

When considering the use of an artery for surgery, important factors include the diameter and the length[234]. Measuring these parameters can therefore aid in the planning for certain cerebral surgeries. The A3 segment is a dominant place for revascularisation procedures, thus adequate knowledge on the diameter, length and possible variations at this site is essential. The number of branches originating from this segment should also be taken into account. Cerebral revascularisation is important for treatment of tumours, intracranial aneurysms and ischemic diseases. Adequate information on the length of possible crossing branches between hemispheres can be crucial for safe surgeries[234].

Few authors have measured the A2, A3 and A4 segments and few divided the results into the left and right sides. Swetha[76] stated that the diameter of the left and right A2 and A3 segments were the same although the length of the left A2 segment and right A3 segments were slightly longer. This was also observed in the present study (Table 5.4). Few studies commented on possible differences bilaterally, between males and females, between different population groups and different age groups. These assessments could possibly indicate patients or populations with a higher risk.

A short vessel with a large diameter provides better blood supply compared to a smaller and longer (more tortuous course) vessel, since blood will take longer to reach the area of the brain it needs to supply. On average (not statistically significant), the A2, A3, A4 segments had largest diameters on the left, in males, in the specimens from the white population group, and in age Group 2. The length was shortest on the left, in females, in the specimens from the coloured population group, and in age Group 1. Thus, the left side showed the only prominent difference in supplying areas of the brain with shorter, larger arteries. On average, the ACA cortical branches had largest diameters on the left, in males, in specimens from the coloured and black population groups, and in age Group 3. The length was shortest on the left, in females, in the specimens from the black population group, and in age Group 2. Thus, the left side and specimens from the black population group showed the only prominent difference in supplying areas of the brain with shorter, larger arteries. Only a few statistically significant differences were observed in the present study and this is tabulated in Table 5.4 and Table 5.5.

Various studies report different average lengths of the ACA cortical branches and this may indicate marked differences between populations groups. Therefore, more population specific studies need to be conducted on the length of these arteries. No triplication or other anomalies were observed in the pilot study, which emphasizes the necessity for a large sample size to ensure that rare variations are observed. Possible differences between populations, sex, bilateral variation, age and population group, may exist. Studies should continue to report on variation in the cerebral vasculature since undocumented variations or anomalies can still be observed. These results should be reported to ensure neurosurgeons are aware of these rare cases of variations and anomalies.

The different ACA segments have been defined and the division of the A4 and A5 segments are described as a point divided close to the coronal suture in lateral view[8]. This cannot be seen in cadaver studies since the brain is removed from the calvarium during the standard procedure (section 4.2, p. 44). Thus, the marker used in cadaver studies can be similar although not identical. The diameter and length of differently conducted studies (cadaver versus angiographic studies) will therefore not be comparable[8]. Cadaver studies do not state which points were used to differentiate the A4 and A5 segments, thus in the present study the midpoint of the corpus callosum was used as a division point between the A4 and A5 segment.

6.1.2. Presence, duplication, and triplication

The presence of the ACA cortical arteries are in accordance with previous studies[2, 3, 14, 16, 17, 21, 22]. Few studies comment on the frequency of the IFA (observed in 31.6% in the pilot study and in 29.8% in the present study) although Ugur *et al*.[2] observed the internal frontal artery in 58.0% of cases (29 cases). The CmA was only observed in 31.6% and 12.4% of cases in the pilot and present study, respectively, although the CmA was observed in 40.0% to 93.4% (Table 2.1)[2, 3, 14-18, 20-26] of cases in the literature. This variability can be due to the different definitions that are used for this callosomarginal artery[25].

Few studies state the duplication or triplication frequencies of the cortical ACA branches[2, 3, 15]. Duplication of the IfO have been observed in 6.0% to 42.0%[2, 3, 15] although the IfO was not duplicated in either the pilot or the present study. When the brain is removed from the head, damage can occur, specifically in the anterior frontal region. Care should be taken to not damage the arteries, specifically the IfO and frontopolar artery. If artefactual damage occurs those specimens should be excluded from the study. This could explain possible differences in the presence or absence of cortical arteries observed by different studies.

6.1.3. Origins

Previous studies have mentioned the origins of the ACA cortical branches[2, 3, 14, 16, 17, 21, 22]. The origins of the cortical branches observed in the pilot and present study are in accordance with previous studies[2, 3, 14, 16, 17, 21, 22], although few studies mention the anomalous origins or common trunks. Cortical branches can occasionally originate from the A1 segment, although this is very rare[235]. The IfO is usually the only cortical branch reported to arise from the A1 segment[235], although anomalous branching of the infra-orbital artery is very rare[236]. Hong[236] observed an IfO arising from the middle third of the A1 segment and stated that this artery can be mistaken for the FpA or the median ACA, since this anomalous artery was larger than usual[236]. Lee and Eastwood[237] observed an IfO that originated from the A1 segment of the contralateral hemisphere. In the present study the IfO and AIFA originated as a common trunk from the A1 segment in one case.

The CmA origin varies considerably and can arise from the A2, A3 or the A4 segment and rarely from the A1 segment[8, 19]. Krishnamoorthy[235] observed a case of the CmA arising from the A1 segment, and Ugur *et al.*[20] observed the CmA and frontopolar artery originating as a common trunk from the proximal A2 segment. In the present study the CmA originated from the AcoA in one case. This can also be viewed as early bifurcation of the ACA into the callosomarginal and pericallosal arteries.

The CmA is defined as an artery that runs near the cingulate sulcus and gives rise to two or more cortical branches. This artery was further classified into an atypical CmA (one or two very short arteries coursing in the cingulate sulcus), and a typical CmA (longer course compared to an atypical callosomarginal artery and usually originates from the A3 segment).

All the callosomarginal arteries observed (in the pilot and present study) coursed in the cingulate sulcus and gave rise to at least two cortical branches. Therefore, all the CmAs had a typical configuration. When a branch gives rise to only the frontal branches (IfO and the FpA excluded), it is referred to as the internal frontal artery. Thus, even though this branch may run in the cingulate sulcus and give rise to two or three branches, it is referred to as the IFA. This distinction is important and is not clearly explained or mentioned in the literature. The most consistent branch to originate from the CmA, is the MIFA[235] and this was observed in the present study.

The CmA originating from the AcoA (one case in the present study) can be wrongly classified as a MedACA. The CmA runs in the cingulate sulcus and not near the corpus callosum sulcus. The median ACA usually runs in the corpus callosum sulcus or above the corpus callosum (observed in all seven cases in the present study). The CmA only supplied one hemisphere, although the MedACA can also be unilateral. If the course of the CmA is not followed, the artery could have been incorrectly classified as a MedACA. This highlights the importance of examining the entire course of the artery or branch.

The IIPA typically originates from the ACA and supplies the inferior third of the precuneus. This artery originated from the posterior cerebral artery in 40.0% of cases in the pilot study, and in 44.6% of cases in the present study. Ladziński and Maliszewski[205] observed both the inferior and superior internal parietal arteries arising from the posterior cerebral artery in one case (1.1%), and the IIPA arising from the posterior cerebral artery in five cases (5.3%). It is normally described that the SIPA and IIPA both supply the precuneus. However, Beevor[238] stated that the most frequent supply of the ACA did not include the precuneus; only the maximal supplied area includes the precuneus. The area most commonly supplied by the PCA included the precuneus, and Beevor[238] observed the posterior cerebral artery supplying the precuneus to the intraparietal sulcus on the medial surface in 40.0% of cases. Van der Zwan *et al*.[75] stated that in certain cases the PCA can supply part of the medial surface normally supplied by the SIPA or IIPA and the boundary between the anterior and posterior cerebral arteries was the parieto-occipital sulcus in only 38.0%.

The IIPA should not be mistaken for the splenial artery. The splenial artery supplies the splenium of the corpus callosum and, according to the literature[88, 199, 203], usually originates from the P2P segment or PoA. The IIPA supplies the inferior third of the precuneus. It is thus important to mention that the IIPA does not necessarily originate as a cortical branch from the anterior cerebral artery; it can originate from the posterior cerebral artery. This also highlights the importance of examining the entire course of the artery or branch.

The IIPA was not a very consistent artery since there was no visible artery in 26.3% (five cases) in the pilot study, and in 30.6% (38 cases) in the present study. The posterior supply of the ACA depends on the extent of the PCA supply and the splenial branches[8]. If there are variations in the anterior cerebral artery, the PCA can supply those areas[76]. Rhoton[8] stated that the IIPA was the least frequent branch and is only observed in 64.0% of specimens. In contrast, Moscow *et al.*[18] observed the IIPA in all cases, often multiple branches.

6.1.4. Anomalies

There were no fenestrations observed in the pilot or present study, although fenestrations of the anterior circulation have been observed by several authors in the literature[32, 36, 47, 53, 55, 56, 58, 62, 68, 74, 99, 103-110, 239]. Insufficient data is available on the frequency and precise location of ACA fenestrations. A large post-mortem study may help resolve this issue[106]. The azygos ACA was not observed in either the pilot or the present study and therefore supports the notion of scarcity. Only a few authors have observed this variation in the literature, usually as a case study[2, 3, 10, 19-21, 24, 36, 47, 49, 51, 53-69, 72, 240, 241]. A few studies mislabelled the azygos ACA as the MedACA, since the azygos ACA can develop due to embryological persistence of the median artery of the corpus callosum. Care should be taken when comparing results from different studies to ensure that the same variation is being compared.

Median anterior cerebral arteries have been observed by numerous authors in the literature[3, 17, 19, 21, 22, 25, 26, 32, 33, 36, 49, 53, 54, 57, 59, 62, 64-69, 76, 78-88, 239, 242]. The MedACA was not observed in the pilot study; however, it was observed in seven cases (11.6%) in the present study. Only four cases were bilateral; therefore the MedACA does not always supply both hemispheres. In 381 specimens, Baptista[54] observed unilateral MedACA in 27 cases, and bilateral MedACA in 23 cases.

Bihemispheric anterior cerebral arteries have been observed by various authors in the literature[14, 15, 19, 20, 22, 25, 26, 36, 54, 61, 74-76]. The bihemispheric ACA was not observed in the pilot study; however, it was observed in 12 cases (19.8%) in the present study. Branches from the left hemisphere gave branches to the right hemisphere in seven cases, and the reverse in five cases. In 381 specimens, Baptista[54] observed branches from the left hemisphere giving branches to the right hemisphere in 25 cases, and the reverse in 20 cases.

The definitions of a MedACA and a BihemACA can be very similar. Bihemispheric ACA is defined as the presence of a branch that supplies the contralateral hemisphere, and the ipsilateral ACA is hypoplastic or terminates early[8, 13-15, 19, 41, 45, 46, 53]. The definition of the MedACA is the presence of an additional branch, and the ACA is still present and not hypoplastic[3, 11, 41, 46, 54, 62, 70, 77]. Additional classification is needed for these anomalies. The definition of the BihemACA state that the ACA of the ipsilateral hemisphere (hemisphere that receives the branch) will terminate early or be hypoplastic. It is important to mention that in the 12 cases of bihemispheric branches, the ACA could terminated at the level of the SIPA (two cases), PLA (five cases), PIFA (one case), MIFA (three cases) or the AIFA (one case). Thus this definition is not necessarily accurate and extended criteria are needed. The following criteria are suggested:

a) If the abnormal artery originates proximal to the first cortical artery, it is considered a median ACA (artery can supply one or both hemispheres, or only one cortical artery).
b) If the abnormal artery originates distal to the first cortical artery and supplies the contralateral hemisphere, it is considered a bihemispheric branch.
c) If the unusual artery originates distal to the first cortical artery and supplies the ipsilateral hemisphere, it is considered a cortical artery with an abnormal origin. Figure 5.12 illustrates the extended criteria of the median ACA, bihemispheric ACA and the unusual cortical artery.

These extended criteria can be illustrated in a comparison between Case 2 (MedACA) (Fig. 5.8) and Case 7 (BihemACA) (Fig. 5.9). Both these cases had an unusual branch that gave origin to the SIPA. In Case 2 (MedACA), the branch originated from the AcoA (thus proximal to the first cortical artery) and was therefore termed a median ACA. In Case 7 (BihemACA) the abnormal branch originated from the level of the first cortical artery, thus the abnormal branch was termed a cortical artery (SIPA) with an unusual origin. There was a BihemACA present, and a bihemispheric and median ACA can be observed in the same specimen, although not in this specific case. Case 1 (MedACA) was also similar to Case 11 (BihemACA). In Case 1 (MedACA) the abnormal artery originated proximal to the first cortical artery and was therefore termed a median ACA. In Case 11 (BihemACA) the abnormal artery originated after the first cortical artery, and was therefore termed a bihemispheric branch.

6.2. MIDDLE CEREBRAL ARTERY

6.2.1. Diameter and length

A shorter vessel with a larger diameter is more efficient at supplying blood. Few studies comment on possible differences that could be observed bilaterally, between males and females, between different population groups and different age groups. On average (not statistically significant), the M1 segment and the inferior, middle and superior trunks had similar diameters bilaterally, and largest diameters in the specimens from the white population group, and in age Group 3. On average, the MCA cortical branches had largest diameters on the left, in females, in the specimens from the white population group, and in age Group 2 and 3. The length was shortest on the right, in females, in the specimens from the black population group, and in age Group 1. Thus, the female specimens showed the only prominent difference in supplying areas of the brain with shorter, larger arteries. Only a few statistically significant differences were observed in the present study and this is tabulated in Table 5.8 and Table 5.10. Literature states that the left hemisphere usually has a growth advantage and that there is left hemispheric dominance[131].

The M1 segment diameter was statistically significantly larger in specimens from the white and coloured population groups, and in the oldest age group. There were no statistically significant differences observed bilaterally or between males and females for the M1 diameter. Similarly, Idowu *et al*.[113] and van der Zwan *et al*.[231] stated that there were no statistically significant differences observed bilaterally in the M1 diameter and Idowu *et al*.[113] stated that there were no statistically significant differences between males and females. Zurada *et al*.[233] stated that the M1 diameter remained constant with age and Tarasów *et al*.[232] stated that the M1 diameter was larger in people older than 40, although this was not statistically significant.

The literature mostly states that the vessel diameters are larger in males compared to females[232]. Tarasów *et al*.[232] did observe larger diameters in males; however, this was not statistically significant. The length of the APA was the only cortical branch to indicate a statistically significant difference between males and females. In females the length was statistically significantly shorter, and the diameter was larger, although not statistically significantly different.

Few studies comment on possible population group differences and the diameter of the CTA was the only cortical branch to indicate a statistically significant difference between the coloured and white population groups. The specimens from the white population group had a statistically significantly larger diameter compared to the coloured population group; however, there were very few specimens in the white population group (eight MCA specimens) in this study.

In the present study, comparison of age indicated the most statistically significant differences between diameter and length of MCA cortical branches. In contradiction to the previous comparisons, these arteries were longer in the older age group, although the arteries had either the same diameter or a smaller diameter. In bilateral and sex comparison, when the diameter or length was statistically significantly different, a side or a sex was usually benefitted. This is not the case with the age groups. A shorter length does not necessarily equal a larger diameter, and *vice versa*. Age-related variation in diameter of vessels can be due to compensative widening due to weakening of the elasticity in the artery wall and presence of atherosclerosis[232]. In the present study, the older group indicated mostly larger diameters compared to the younger age group.

6.2.2. Predivision length

Confusion exists on the classification of the M1 segment, in particular the distinction of the M1 segment from the M2 segment[112]. The M1 segments can be defined as the part from the origin of the MCA to the main bifurcation, or this segment can be defined as the part from the origin of the MCA to the genu (division or no division present)[124]. Thus, the M1 segment length and predivision length is not always the same, and this can lead to confusion and data to be incomparable. In Table 5.9, the length is considerably different between certain studies. The predivision length was between 13.0 mm and 23.4 mm[112, 113, 116, 123, 124, 128, 231-233]. The authors should always state which definitions are being used.

In certain cases in the present study, the predivision length was very long. It should be considered that after a certain length, the MCA branching can be classified as monofurcation. Grellier *et al*.[116] described monofurcation as branching after the limen insulae. However, using different definitions could cause the frequency of monofurcation to be incorrectly described in the literature. Authors should describe the criteria and definitions that are used to ensure the results are comparable.

6.2.3. Absence, duplication, triplication

The most commonly absent artery was the common temporal artery in 65.0% (13 cases) in the pilot study and 51.0% (51 cases) in the present study. The most commonly duplicated branch was the anterior parietal artery in 30.0% (six cases) in the pilot study and 9.0% (nine cases) in the present study. Bradac[13] reported that the APA is usually a single branch. In the present study the central artery was also commonly duplicated (8.0%). Salamon and Huang[27] stated that duplication of the central artery was almost constant. No triplication was observed in the pilot study and the only triplicated arteries in the present study were the central and angular arteries in one case each. Very few studies report on absence, duplication and triplication of the MCA cortical branches. Therefore, a complete description is given in Table 5.11.

6.2.4. Origins

When bifurcation was observed in the pilot and present study, the superior trunk usually gave origin to the OfA, PfA, precentral, and the central arteries. The parietal and angular arteries originated from either the superior or the inferior trunks. The inferior trunk gave origin to the temporal and temporo-occipital arteries. This is consistent with previous reports[8, 11, 13, 27, 114, 121, 123, 132].

True trifurcation was only observed in the present study in six cases. When trifurcation was observed, the superior trunk usually gave origin to the OfA, PfA and precentral arteries. The middle branch gave origin to the central artery (three cases), APA (five cases) and PPA (three cases). The PcA and angular arteries originated from the middle trunk in one case each. The inferior trunk usually gave origin to the temporal, temporo-occipital and angular arteries. These findings are consistent with previous reports[8, 11, 13, 27, 114, 121, 123, 132].

Few studies mention distinct origins, and although authors commonly state that cortical branches can arise from common trunks, few studies discuss the prevalence of these common trunks[132]. The common trunks were described in detail in the results section 5.2 (p. 54) and 5.5.2.3. (p. 83). It is noteworthy to mention the definition of a common trunk. A common trunk was defined when the arteries bifurcated, and one artery did not arise from the other artery. A common trunk typically bifurcates at almost a 90 degree angle and the cortical branches have similar diameters. This is not always defined in the literature and could lead to inaccurate results. Furthermore a cortical branch could originate from another cortical branch, and this has not been discussed in previous studies.

6.2.5. Early branches

Cortical branches that arise from the main MCA trunk before the initial branching are referred to as early branches. Early branches were observed in the present study in 85.0% of cases. Most authors only state that early frontal or temporal branches were present, although the specific cortical branches that arose as early branches are rarely mentioned. Meneses *et al.*[123] stated that the TpA originated as an early temporal branch in 80.0%, the ATA in 40.0%, the orbitofrontal artery in 30.0%, and the middle and posterior temporal arteries in 20.0%. Idowu *et al*.[113] stated that the only early temporal branch was the TpA and the only early frontal branch was the OfA. In the present study the OfA, PfA, temporopolar artery and anterior temporal artery frequently arose as early branches.

6.2.6. Branching

Eleven branching subtypes can be distinguished from the literature. Most authors do not specify the different branching subtypes. The only branching types usually mentioned include bifurcation, trifurcation, monofurcation and tetrafurcation. The definitions used to classify the branching types need to be equivalent; otherwise the results will not be comparable. In Figure 2.6 (section 2.2.2, p. 22) these 11 branching subtypes are described in detail, to ensure that future studies will not report incorrect results. When definitions are adequately described, future studies can be compared to ascertain possible differences in sex, population group and different age groups.

Tanriover *et al*.[114] stated that in the trifurcation cases observed, the middle trunk gave rise to either one or two arteries. This was also observed in the present study (two arteries in four cases, three arteries in two cases). The middle trunk never gave rise to just one artery, although it is noteworthy that the superior trunk in certain trifurcation cases only gave rise to one artery (the calcarine artery in two cases). This could be perceived as the cortical branch arising with a large diameter at the bifurcation region. Currently only the branching region is being taken into account when the branching type is classified and not the arteries that the trunks give rise to.

Ugur *et al.*[20] stated that the middle trunk was observed in 75.0% of cases, although the authors further elaborated that this middle trunk originated from the superior trunk in 62.5% and from the inferior trunk in 12.5%. This shows that true trifurcation was not observed, and it is more likely that the authors observed pseudotrifurcation, medial or lateral trifurcation. Not all authors give further description of the trifurcation cases. Most studies do not state the distances used to define these branching types. Only the terms “close,” “near” and “the impression of branching” are used as terminology. Ciszek *et al*.[133] stated that a second early temporal branch with a large diameter can create a “false bifurcation” and Vuillier *et al*.[124] stated that the cortical branches can be mistakenly classified as branching. Pseudobifurcation is described as only medial pseudobifurcation and pseudobifurcation. The term “lateral” was added to avoid confusion. Since the previous authors did not state the criteria, this was determined in the pilot study (section 5.2, p. 52).

Early branching was classified when the first major division occurred at 5 mm or less from the MCA origin[117-120]. Only one case (1.0%) in the present study fits these criteria and therefore it should be considered to modify this definition to branching before 8 mm or even 10 mm. If these modified criteria are used (branching before 8 mm), then the frequency of early branching would have been 7.0%. This is still in the reported frequency as described in the literature by previous authors. Early branching has been observed in 2.6% to 11.3%[32, 82, 118, 119, 131] of cases. Authors need to state what is considered as early branching, and possibly give the length of each case observed. Therefore future studies can adjust the observations to compare the literature with their results.

Few studies fully describe the MCA branching subtypes and very few studies comment on possible differences between males and females, the left and right side, different population groups and different age groups. In the present study, there was a statistically significant differences between the branching subtypes in comparison between males (n=68) and females (n=32). Idowu *et al*.[113] observed no difference in the branching pattern between males and females.

6.2.7. Anomalies

Several authors have observed an accessory MCA[6, 7, 32, 33, 36, 55, 56, 82, 99, 105, 106, 113, 114, 116, 121-123, 130, 145, 147, 148, 150, 154, 158, 159, 183, 243-247], a duplicated MCA[6, 32, 33, 116, 118, 119, 122, 123, 130, 131, 134, 142-151, 171, 172, 244, 248], and fenestration of the MCA[58, 93, 107, 120, 122, 124, 125, 145, 148, 150, 161, 168, 239, 249]. In the pilot and present study an accessory, duplicated or a fenestrated MCA were not observed. This demonstrates the necessity for larger studies on the MCA, since these variations are extremely rare. There is a gap in the literature regarding data on the MCA anatomy and variations, and more data should be obtained on the diameter, length, and the area supplied by these anomalies.

Very few details are given on the diameter and area supplied by the duplicated MCA. The diameters of the duplicated MCA have been documented as 1.4 mm and 3.5 mm by Meneses *et al*.[123] and Umansky *et al*.[122], respectively. Meneses *et al*.[123] stated that the duplicated MCA supplied the temporopolar artery and the ATA. Few details are given on the diameter of the accessory MCA and this has been documented as 1.1 mm to 1.6 mm[122, 123, 158]. Kim and Lee[154] stated that in 18.8% the diameter of the accessory middle cerebral artery was similar to the main MCA trunk, and in 81.3% it was smaller compared to the main MCA trunk.

The accessory MCA arises from the anterior cerebral artery, however, few authors state the precise origin. It has been observed arising from the A1 segment[116], near the AcoA area[158, 245], the proximal A1 segment[154], the middle A1 segment[154], the distal A1 segment[154], and the A2 segment[154]. Studies may confuse the proximal and distal A1 segments. The proximal part is closest to the origin of the A1 segment (at the connection of MCA) and the distal A1 segment is closest to the origin of the AcoA.

Few authors state which cortical branches are supplied by the additional branch or what area is supplied by the additional vessel. The AccMCA usually supplies the frontal region and the DupMCA the temporal region. The accessory MCA generally gives rise to the orbitofrontal artery and PfA[246], and the duplicated MCA to the TpA, anterior and middle temporal arteries[143]. Other cortical branches that have been supplied by the accessory MCA include the RaH[123], precentral artery[154, 246, 250], central artery[154, 246, 250], APA[154]. It is extremely important to state the precise origin, course and diameter of the accessory and duplicated MCA since this information is helpful to neurosurgeons[139]. The duplicated MCA is more scarce compared to the accessory MCA and few authors mention the areas supplied by the duplicated MCA.

Fenestration of the MCA is usually described to have three main subtypes, proximal, intermediate and distal fenestration, however, studies do not always state if this refers to fenestration at the M1 segment, since fenestration can also be observed at the M2 segment. Fenestration of the MCA was observed in 0.1% to 5.8% (Table 2.7)[53, 58, 93, 107, 120, 122, 124, 145, 148, 150, 161, 168] in the literature.

If the branching or origin is slightly different from the normal definition, this should be thoroughly explained. This ensures that future studies using different or elaborated definitions can still be compared to previous work. For example, the accessory MCA was first described as an artery arising from the ICA or anterior cerebral artery. This definition was later altered; the term accessory MCA only refers to an artery arising from the anterior cerebral artery, and the term duplicated MCA was used for an artery originating from the ICA[117]. In later studies the DupMCA was further elaborated into two subtypes, Type A arises at the top of the ICA (more distal origin), and Type B arises between the top of the ICA and anterior choroidal artery (more proximal origin)[141-143]. Therefore, if previous authors and earlier studies described the anomalies thoroughly, the data can be compared to later studies. The different MCA anomalies are explained in section 2.25 (pp. 25-30) and a detailed line diagram is provided (Fig. 2.8) to ensure that future studies give adequate information on the anomalies that are observed. To compare the results of studies, the definitions that are used for the anomalies should always be reviewed.

6.3. POSTERIOR CEREBRAL ARTERY

6.3.1. Diameter and length

A shorter vessel with a larger diameter is more efficient at supplying blood. Few studies comment on possible differences that could be observed bilaterally, between males and females, between different population groups and different age groups. On average (not statistically significant), the P1, P2 and P3 segments had larger diameters on the left, in males, in the specimens from the white population group, and in age Group 3. The length was shortest on the left, in females, in the specimens from the coloured population group, and in age Group 1. Thus, the left side showed the only prominent difference in supplying areas of the brain with shorter, larger arteries. On average, the PCA cortical branches had larger diameters on the left, in males, in the specimens from the white population group, and in age Group 2. The length was shortest on the left, in females, in the specimens from the coloured population group, and in age Group 1. Thus, the left side showed the only prominent difference in supplying areas of the brain with shorter, larger arteries and the literature does state that the left side is usually benefited[131]. Only a few statistically significant differences were observed in the present study and these are tabulated in Table 5.14 and Table 5.15.

Zeal and Rhoton[199] stated that the P2A and P2P segments were each approximately 25.0 mm in length. In the present study the P2A and P2P segments were 39.0 mm and 13.4 mm, respectively. This difference could be due to variances in definition of the P2A and P2P segments. Few studies mention the PCA segment lengths; therefore this comparison may be biased. Authors should always state how the segments were defined and measured.

The diameters were similar in the literature, and this was most likely since the same part is usually used to measure the diameter (at the origin of the segment or branch). Not all authors state the part that was measured and this could lead to incomparable results. Very few studies give separate data of the right and left sides, and none give information on sex, age, or population group. This makes it impossible to compare the results with previous studies.

6.3.2. Absence, duplication, triplication

The CTA was observed in only six cases (30.0%) in the pilot study and 34 cases (27.4%) in the present study, which is consistent with the literature. The presence of the CTA was 16.0%[199], and 20.0%[204] in the literature, thus the CTA is not consistent. The AITA was observed in 15 cases (75.0%) in the pilot study and in 119 cases (96.0%) in the present study. The PITA was observed in 19 cases (95.0%) in the pilot study and in 123 cases (99.2%) in the present study. This is consistent with the literature. The presence of the MITA was reported in the literature as 20.0%[204] and 38.0%[199]. The MITA was observed in 19 cases (95.0%) in the pilot study and in 114 cases (91.9%) in the present study. This artery is described as not very consistent, although this cortical branch was observed in most hemispheres. The PoA and calcarine artery was observed in all cases in the pilot and present study, which is consistent with the literature[199, 201, 202]. The presence of the splenial artery was reported in the literature as 90.0%[201] and 100%[88, 199]. However, the splenial artery was observed in only four cases (20.0%) in the pilot study and in 45 cases (36.3%) in the present study.

6.3.3. Origins

The CTA originated from the P2A segment in all cases observed in the pilot and present study. The most common origin is reported in the literature as either the P2A or P2P segment[199, 204]. A common temporal artery was defined when the arteries bifurcated, and one artery did not arise from the other artery. A common trunk typically bifurcates at almost a 90 degree angle and the cortical branches have similar diameters. This is not always defined in the literature and could lead to confusion and inaccurate results. The most common origin of the AITA and MITA was the P2A segment in the literature[199, 204]. The most common origin of the PITA in the literature was the P2 segment[196, 202] and P2P segment[199, 204]. The most common origin of the temporal arteries was the P2A segment in the pilot and present study. The most common origin of the calcarine artery and PoA was the P3 segment in the pilot and present study, although the PoA and calcarine artery can originate from the P2P, P3 or P4 segment. Thus the results from the pilot and present study are similar to the descriptions in the literature.

The most common origin of the splenial artery was the PoA in the pilot and present study. In the literature, the splenial artery also originated mostly from the PoA[88, 199, 201]. The prevalence observed in comparison to previous studies varies tremendously. The IIPA originated from the posterior cerebral artery in 40.0% of cases observed in the pilot study, and in 44.6% of cases in the present study. It is possible that the studies mistermed the IIPA as the splenial artery. The IIPA supplies the inferior third of the precuneus and the splenial artery supplies the splenium of the corpus callosum. This is further described in section 6.1.3. (p. 109). The area supplied by the artery should be taken into account, not just the origin.

6.3.4. Branching

The end of the main trunk was previously described as the branching of the common temporal artery; however, the main branching is now described at the origin of the calcarine and parieto-occiptal arteries. This point is also used when refering to the main branching point; however, this configuration was only observed in one case (5.0%) in the pilot study and 34 cases (27.4%) in the present study. The first branching (main bifurcation) was due to origin of the CTA in six cases (30.0%) in the pilot study and 25 cases (20.2%) in the present study. Furthermore, the main bifurcation was due to origin of the PITA in eight cases (40.0%) in the pilot study and 52 cases (41.9%) in the present study. Trifurcation can also be observed. A branching before the division of the PoA and calcarine artery was present in most cases. This shows that the main branching point of the PCA should be reconsidered and should be mentioned in subsequent studies.

Since the main branching of the PCA is described as the division between the PoA and the calcarine artery (end of the main trunk), this level is usually noted in previous studies. This division level was reported in in the present study (section 5.2.3, p. 100). The PoA and calcarine artery typically originate at the P3 segment, although the branching can occur at the P2 or P4 segments[205]. Studies usually only comment on the branching point of the PoA and calcarine artery and not whether a branching was observed before this division.

It should be noted how branching is classified, since it is not just a large vessel originated from the main stem. A visible splitting of the main trunk is seen into either two or three branches (as can be seen in the branching of the middle cerebral artery). The branching is usually at a 90 degree angle and the vessels have a similar diameter.

6.3.5. Anomalies

There was one case of fenestration in the pilot study and two cases of fenestration in the present study. Fenestrations of the PCA are typically observed in the P1 segment, although not as often in the P2 segment. All three fenestrations were located in the P2A segment (two left side, one right side). Fenestrations of the PCA are not very common and fenestrations are usually observed in the AcoA or basilar arteries. Fenestration of the PCA was observed by various authors[53, 99, 105, 107, 118, 161, 197, 211-218] in previous studies. Few authors give more information other than the presence of the fenestration.

The fenestration observed in the pilot study (Fig. 5.2) and the first case described in the present study (Fig. 5.21A) was similar and can be seen as two arteries originating nearby and then merging. The definition of fenestration is incomplete duplication, which implies one common origin of an artery which split into two and re-joins[46, 58, 92-94]. This is not the case with these two cases (fenestration 1 and fenestration 1A). Two arteries seem to merge, not split. The second fenestration case (slit-like) represents a typical example of incomplete duplication. The artery split into two parts, and re-joined. Fenestration was the only true anomaly of the PCA that was observed in either the pilot or present study.

6.4. LIMITATIONS

Rare anomalies were not always observed in the pilot or present study, therefore, a limitation of this study was the sample size. A larger sample size could ensure that rare variations and anomalies are observed. A total of 136 hemispheres were used, which is more compared to most of the previous studies.

In all autopsy studies there is a risk of artefactual damage to the specimens. Damage can occur to the brain and arterial system during the removal of the brain. If there is damage, those specimens should be excluded to avoid misrepresentation of cortical branches. Decomposition is also possible, and if decomposition is extreme those specimens should be excluded.

Autopsy studies measured the external diameter of the arteries, and in MRA studies the internal diameter is measured. Thus there can be a difference in reported diameter and the results of these different types of studies cannot be compared.

Studies conducted with the use of MRA also have limitations including certain smaller vessels not being detected[232]. Cadaver studies may be useful in observing these smaller vessels, although the presence of blood or blood clots may obstruct flow of the dyes causing the arterial systems to not fill properly[251]. Possible anastomoses between cerebral arteries and cortical branches were studied, although the coloured silicone did not always reach to the end of the artery. If the supply of a specific branch or cerebral artery is investigated, it is important that the medium is injected into the arteries at same time, with the same pressure for adequate visualisation of the supply of each artery[238].

Subtle differences can also be evident between autopsy studies using different materials or dyes and the consistency of the material or dyes can influence the results. Thinner fluids may fill smaller vessels more effectively, although thicker mediums that solidify allows for better investigation of the arterial system. A range of media have been used (described in section 4.3. p. 45)[251].

CHAPTER SEVEN

CONCLUSION

Knowledge of the anatomy of the cerebral arteries is essential in vascular procedures, for example aneurysm and arteriovenous malformation surgery[5]. In addition, information on the anatomical pattern of the cerebral arteries is essential in interpretation of clinical signs of a stroke[17, 121]. Furthermore, aneurysms can be observed at the branching of cerebral vessels, highlighting the importance of a thorough knowledge of the vascular anatomy[5, 7, 14, 119, 252]. Moreover, obliteration of an arterial segment can cause unwanted or unexpected clinical consequences due to variations in the pattern of cerebral arteries[17, 42]. Variation of the length is important in neurosurgical procedures, since a shorter trunk may play a role in aneurysm formation. Changes in vessel diameter could also indicate early signs of several pathological conditions[49].

In a comparison between the ACA, MCA and the PCA, the anterior cerebral artery has been thoroughly studied. However, there are still aspects that have not been adequately investigated. The average diameters, lengths and origins of the ACA cortical branches are described by selected studies, although the common trunks are not described in the literature. This was done in the pilot and present study.

The ACA variations are described in the literature, although additional criteria were still lacking. This was described in the results section of the present study. Most studies only mention the presence of ACA anomalies and few authors give further information on these anomalous arteries. A thorough investigation was conducted on the prevalence of these anomalies, and in the present study, more information was given on the origin, diameter, length and area supplied by these anomalous branches.

The average diameters, length and origins of the MCA cortical branches are not adequately described in the literature. Possible common trunks are also not thoroughly reported in the literature. These aspects were reported on in the pilot and present study. The anatomy of the temporal superior arteries have been scarcely documented, thus a detailed description was given on the anatomy of the temporal superior arteries.

The MCA branching types are discussed in previous studies, although the different subtypes are usually neglected; only bifurcation and trifurcation are usually noted. An illustration of the different subtypes is given in the literature review since there is still confusion on these subtypes. The criteria for each subtype has also not been previously described, thus this was noted in the pilot study.

The MCA anomalies are described in the literature and an illustration of these anomalies are given in the literature review. Most studies only mention the prevalence of the anomalies, and this was tabulated in the literature review. Not enough information is given when these MCA anomalies are observed, thus an illustration was given to ensure future studies can adequately describe these anomalies.

In comparison to the anterior and middle cerebral arteries, the PCA is the most neglected cerebral artery. The average diameters and lengths of the PCA cortical branches have not been described, and origins have only been mentioned in selected studies. Therefore, this was done in the pilot and in the present study. This study proposes a revised classification of the inferior temporal arteries, which excludes the hippocampal arteries, and takes into account the origins of the inferior temporal cortical branches of the PCA. Therefore, the configuration of the temporal arteries was also discussed in detail. The branching pattern has been described as the main branching between PoA and calcarine artery. This was not the case in the majority of cases. Therefore the branching pattern was re-evaluated and described as monofurcation, bifurcation and trifurcation.

The PCA anomalies have been described in the literature and an indication on the prevalence is given in the literature review. Fenestration of the PCA is very rare, although one case was observed in the pilot study and two cases in the present study. Digital images of these fenestration were provided to contribute to the knowledge on these anomalies.

Possible differences between age, population groups, sex and bilateral variation regarding the diameter and length of the cerebral segments and cortical branches are, to the author's best knowledge, not mentioned or poorly reported in previous studies. Therefore in the present study a detailed analysis was done to indicate possible statistically significant differences. The ACA and PCA segments and cortical branches usually indicated larger diameters and shorter lengths on the left side and the MCA cortical branches showed larger diameters and shorter lengths in females. The pilot and present study also reported on the origins, absence, duplication and triplication of the cortical branches, since limited research with regard to these aspects have been conducted.

The brains were obtained from Stellenbosch University and from a Western Cape population. To the author's best knowledge, no studies of this nature have previously been completed on a Western Cape population or in South Africa. Given the important implications that the anatomical variation of the cerebral arteries may have, future research should focus on giving a more comprehensive description of the anatomy.

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